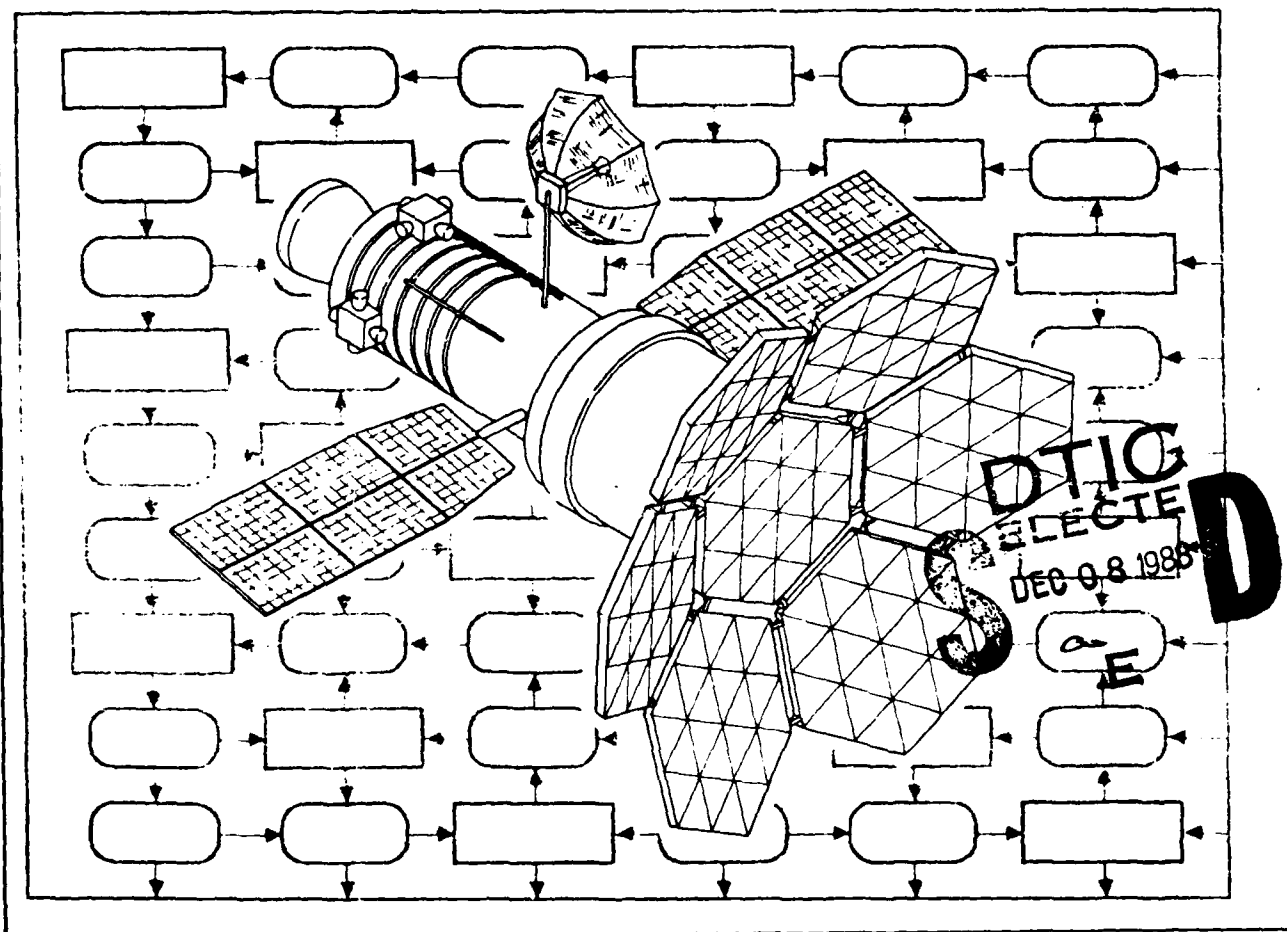


Experimental Verification of an Innovative Performance-Validation Methodology for Large Space Systems



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HARRIS CORPORATION GOVERNMENT AEROSPACE SYSTEMS DIVISION

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<p>A technology gap exists in verifying performance of large space systems. To fill that gap the proposed program seeks to develop and validate an efficient pre-flight performance verification methodology. The approach involves selective component testing along with analysis of subsystem interactions. The methodology exploits MEOP (Maximum Entropy/Optimal Projection) Control-System Design and Majorant Robustness Analysis. The approach will be formulated for several representative large space systems and experimentally verified on a 3-meter diameter multi-hex panel ground-based active controls testbed.</p>													
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First Annual Report

Experimental Verification of an Innovative Performance- Validation Methodology for Large Space Systems

For
Department of the Air Force
Air Force Office of Scientific Research (AFSC)
Bolling Air Force Base, DC 20332-6448

Attention:
Anthony K. Amos
Program Manager
Directorate of Aerospace Sciences

September 1988

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**Experimental Verification of Innovative Performance
Validation Methodology for Large Space Systems (EVM)**

Annual Report No. 1

Contract: F49260-87-C-0108

Principal Investigator: Dr. D. C. Hyland

1. Technical Background

The size of SDI space systems poses significant new challenges to traditional pre-launch performance validation. Because of the inability to test large lightweight structures in an ambient environment, there exists a technology gap in verifying performance of large space systems. What is needed to fill that gap is a systematic methodology for planning a combined analysis and testing qualification program that will result in maximum preflight performance prediction accuracy at minimal cost. This program aims to fill that technology gap by developing and validating an efficient preflight performance-validation methodology for large space systems.

The approach involves selective component testing along with analysis of subsystem uncertainties and interactions. The methodology exploits MEOP (Maximum Entropy/Optimal Projection) control system design and Majorant Robustness Analysis. The innovative design and analysis methods also incorporate the breakthrough discoveries of Bernstein and Haddad which allows optimal H_{∞} design with constraints on controller complexity. In the applications of MEOP/Majorant techniques, a large space structure is modelled as a collection of interacting subsystems with subsystems and interaction uncertainties. Majorant Analysis identifies subsystem components and subsystem interaction which contribute critically to prediction uncertainty. Selective hardware testing thus efficiently reduces model uncertainty for refining MEOP control-system designs. Using this rationale, we experimentally test the methodology using the Harris multi-hex prototype (MHPE) ground based active controller testbed. The consideration of deployability requirements dictated by SDI large optics aperture size specifications has not heretofore been included in SDI structural control experiments.

2. Objectives/Program Tasks

The objectives of this study are attained by the accomplishment of the following general tasks:

1. Characterize subsystem uncertainties (using MHPE as benchmark).

2. Develop test sequence plan and perform initial check of majorant analysis on MHPE.
3. Identify and test critical components.
4. Perform full-up verification using MHPE tests.

The task flow is illustrated in Figure 1.

3. Progress To-Date

First, it should be noted that laboratory testing on this program presumes the use of the MHPE vibration control testbed, which was fabricated under the Harris FY'88 Precision Structures and Control IR&D program. At the present time the MHPE structure and control actuators have been completely fabricated. As indicated in the Task flow schedule of Figure 2, the MHPE apparatus was ready for testing in mid March 1988 and initial testing began in May 1988. Thus the primary test apparatus exists and remains continuously available for test activities during the remainder of this program.

Activities within Tasks 1 and 2 of this program are to construct the nominal dynamical model of the MHPE test apparatus, identify and quantify the most significant a priori modelling uncertainties and use MEOP and Majorant Analysis tools to obtain a baseline active structural control design and associated bounds on performance predictions.

The above tasks have been completed. Our survey of likely modelling uncertainties is summarized in Table 1. It was found that the most important source of modelling uncertainty is the variation, within manufacturing tolerances, of the thickness of the joint plates which tie together the adjacent hexagonal panels of the MHPE mirror array. Such thickness variations can cause over 10% variations in the predicted modes.

Table 1

Modelling Uncertainties in the MHPE Apparatus

Component	Error Source	Relative Importance
Sensors (Accelerometers)	• Bias, Scale Factor, Misalignment, Hysteresis, Non - Repeatability (See Accompanying Table)	Either Unimportant In Regime of Application or Remediable via Compensation & Calibration
	• Electronics Noise	Important - Sets "Noise Floor" on Performance (Explicitly Included in Analysis & Design Models)
LPACT Actuators	• Accelerometer Error Sources	Relatively Unimportant (See Accompanying Figure) Because Most Error Sources Are Compensated by Internal Force Control Loop.
	• Electronics Variations Due to Thermal Effects	Electronics Noise (Explicitly Included in Models) <u>is</u> Important to Overall Perf.
	• Mech. Fab. Tolerances	Accelerom. Mismatch Remedied by Initial Calibration
	• Thermally Induced Mech. Properties (Flexure Stiffness Variations)	
Structure	• Manufact. Tolerance On GRE Tube Thickness	Small Absolute Errors Unimportant For Lower Frequency Modes
	• Aluminum Joint Fittings	Moderately Important For Higher Modes
	• Epoxy Bond Strength	
	• Manufacturing Tolerance On Thickness Of Joint Plates Nominal Thickness = 0.15 in Tolerance: ± 0.050 in	Very Important - Significantly Affects Even the Lowest Modes

Using our design and analysis tools we have designed a MEOP vibration control algorithm which maintains good performance despite off-nominal joint plate thickness variations. Figure 3 shows how, under two different controller designs, the mirror panel optical quality (dephasing) degrades as a function of off-nominal joint plate thickness variations of magnitude "DELTA". The manufacturing tolerance is indicated by the dashed line in Figure 3. Note that a standard Linear Quadratic Gaussian (LQG) controller design can drive the closed loop system unstable under worst-case thickness variations. In contrast, the MEOP design maintains excellent performance improvement relative to the uncontrolled structure despite worst-case thickness variations.

Within the concluding portion of Task 2, experimental tests of the complete MHPE apparatus were conducted in order to refine the nominal dynamics model and to update the initial estimates of the performance impact of residual modelling uncertainty and manufacturing nonuniformity. Appendix A gives a description of the MHPE apparatus, details of the system dynamic model and a selection of system test results. Based on these test results, we have initiated (in accordance with Task 3) the testing of selected subsystems in order to further reduce uncertainty and achieve refined performance. Subsystem tests include dynamic testing of structural subassemblies and bench testing of actuator and sensor hardware - particularly in the high frequency range, 1-5KHz.

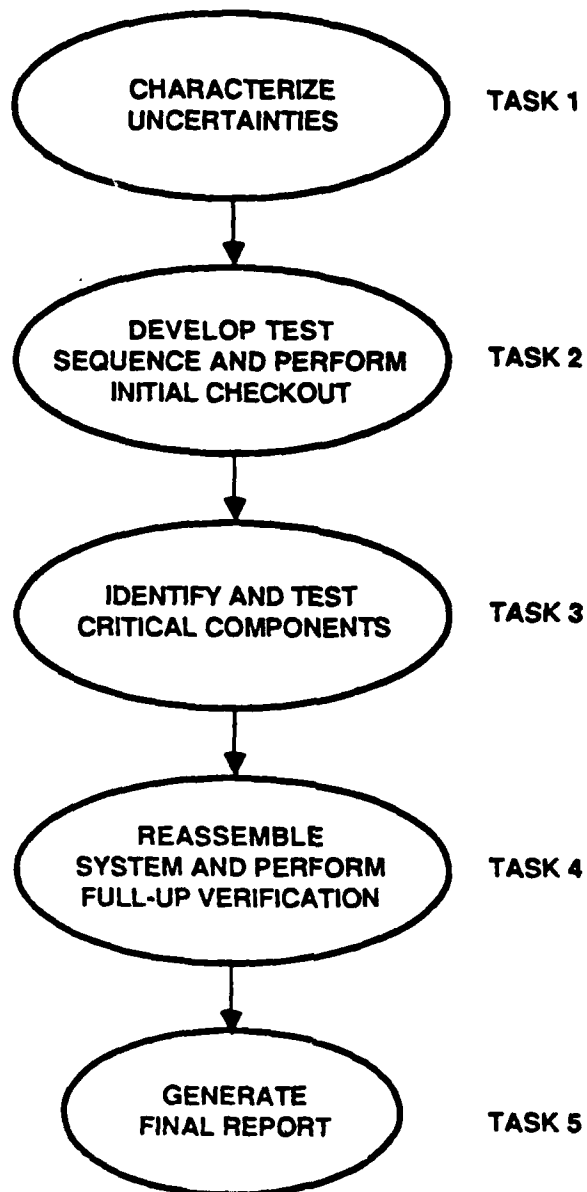
In summary, with the completion of Tasks 1 and 2 and the initiation of Task 3, the program is on or ahead of schedule.

Additionally, in the course of the above activities, significant progress has been made in the application of the Majorant Robustness Analysis tools utilized for this program. In particular, Majorant Analysis has been effectively applied to the time-domain analysis of prediction errors in system transient response. The highlights of these developments, together with an illustrative example of practical importance are given in Appendix B.

Descriptions of the MHPE apparatus, MHPE modelling and test results and developments in Majorant Analysis obtained within this program are also reported in numerous conference presentations and archival journal publications that have appeared or will appear in the near future or are in review. Appendix C contains an up-to-date listing of these presentations and publications.

4. Research Progress Forecast

Referring to Figure 2, subsystem component tests will be conducted over the next several months to reduce the most critical a priori modelling uncertainties. This date provides the basis for refined predictions and a "tuned" MEOP controller design. A full-up test of this tuned design is planned for mid-January 1989. At this point, we shall have demonstrated one full iteration of our innovative pre-flight system validation methodology.



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Figure 1. The Task Flow Involves Methodology Formulation for Representative Systems Followed by Methodology Validation for the Multi-Hex Testbed

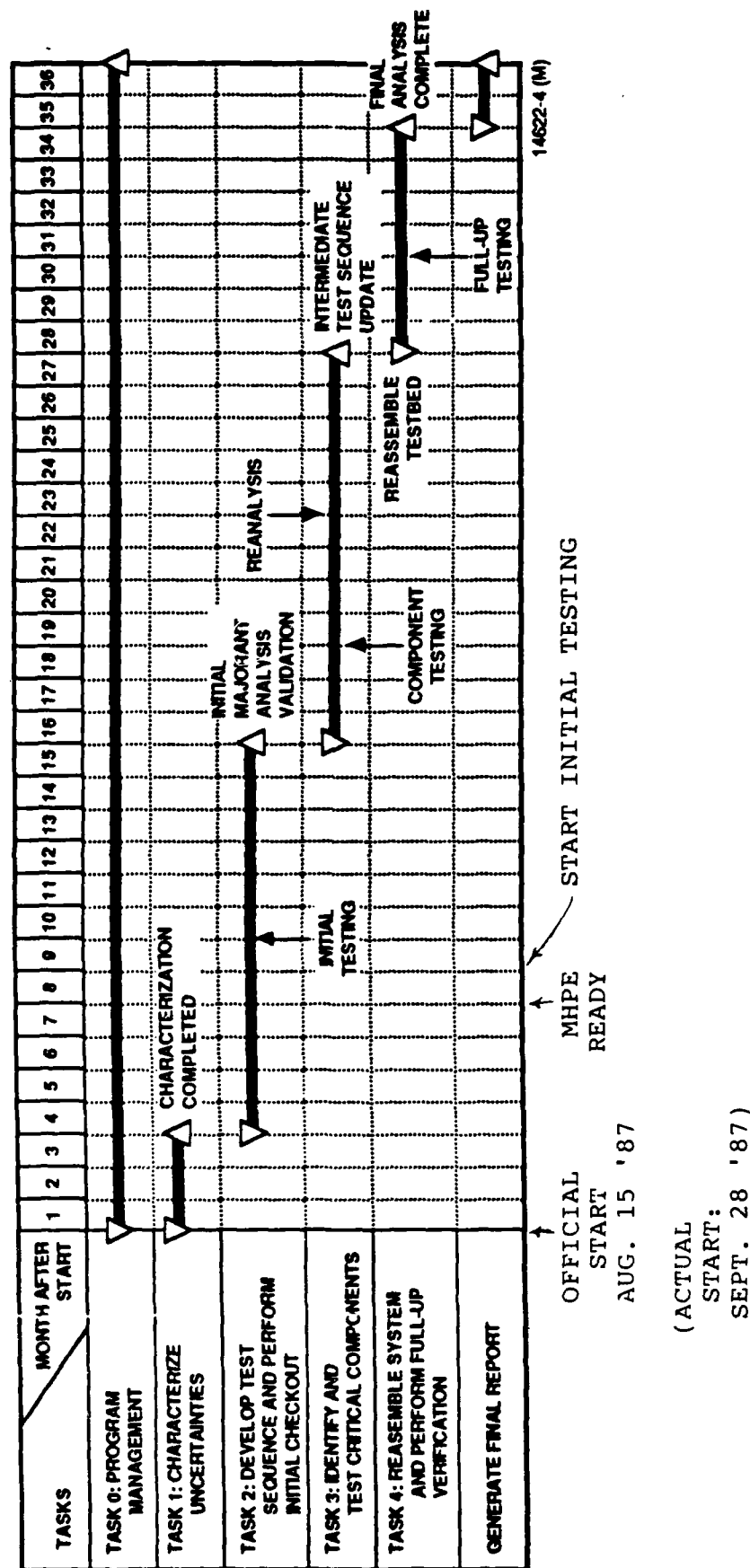


Figure 2. Task Schedule

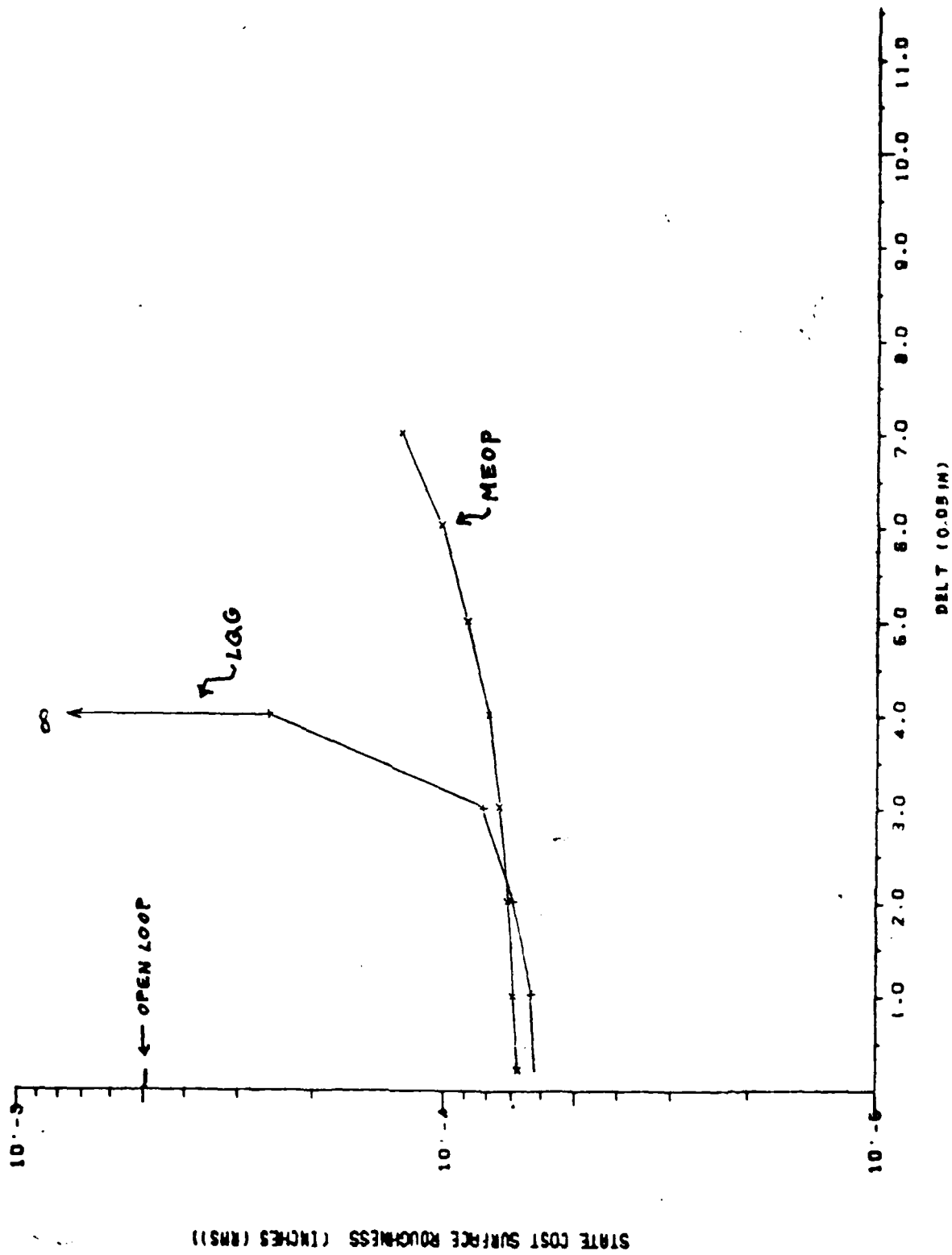


Figure 3

Appendix A

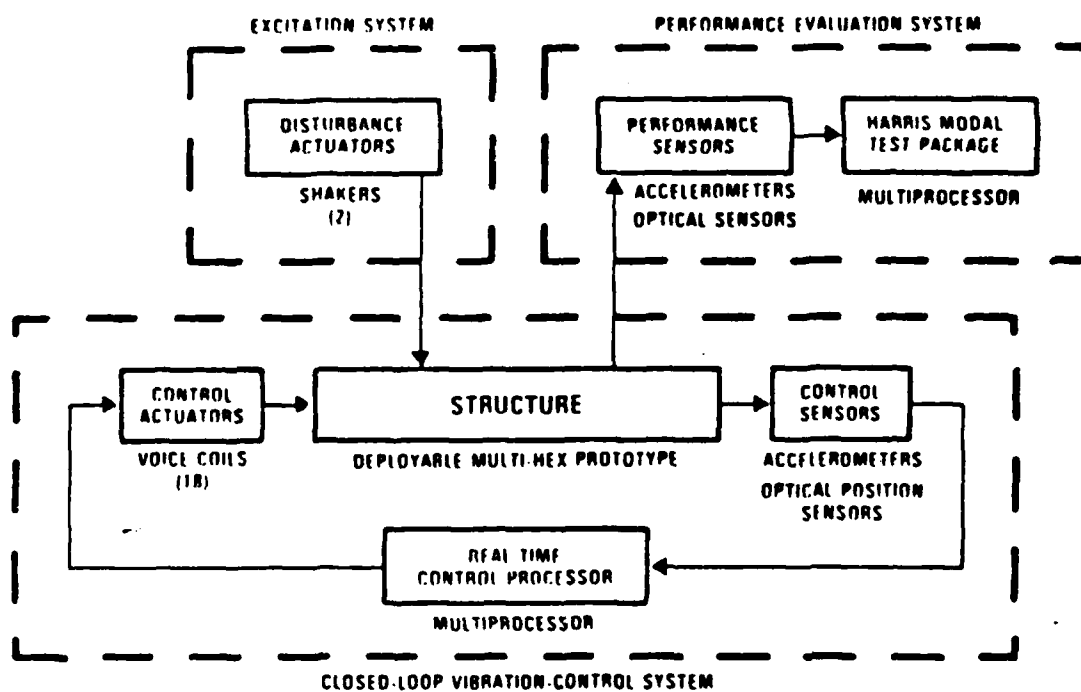
**EVM PROGRAM ACCOMPLISHMENTS:
FULL-UP DEMONSTRATION OF ACTIVE STRUCTURAL
CONTROL FOR PRIMARY MIRROR OPTICAL PERFORMANCE**

To-date the EVM program has entailed the following tasks:

1. Perform open-loop tests and system identification of the Multi-Hex Prototype Experiment (MHPE) apparatus
2. Characterize system dynamics uncertainties, perform initial Majorant Analysis and develop a highly robust MEOP control design for the MHPE
3. Perform closed-loop MHPE tests using the initial MEOP control design

The accomplishments of these tasks has produced the first experimental verification of structural control ever achieved for a large structural test-bed of representative complexity. This result advances SDI objectives by showing how active vibration control can be used to suppress Primary Mirror dephasing error induced by broad-band vibration—thereby improving far-field optical performance without the weight penalties of undue structural stiffening.

In the following Figures and accompanying narrative, we review the MHPE test setup and the test results.



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Figure 1. The Overall MHPE Test Facility Consists of the Structure, Actuators and Sensors, Disturbance and Isolation Systems and On-Line Computer for Control Implementation and Data Acquisition and Analysis.

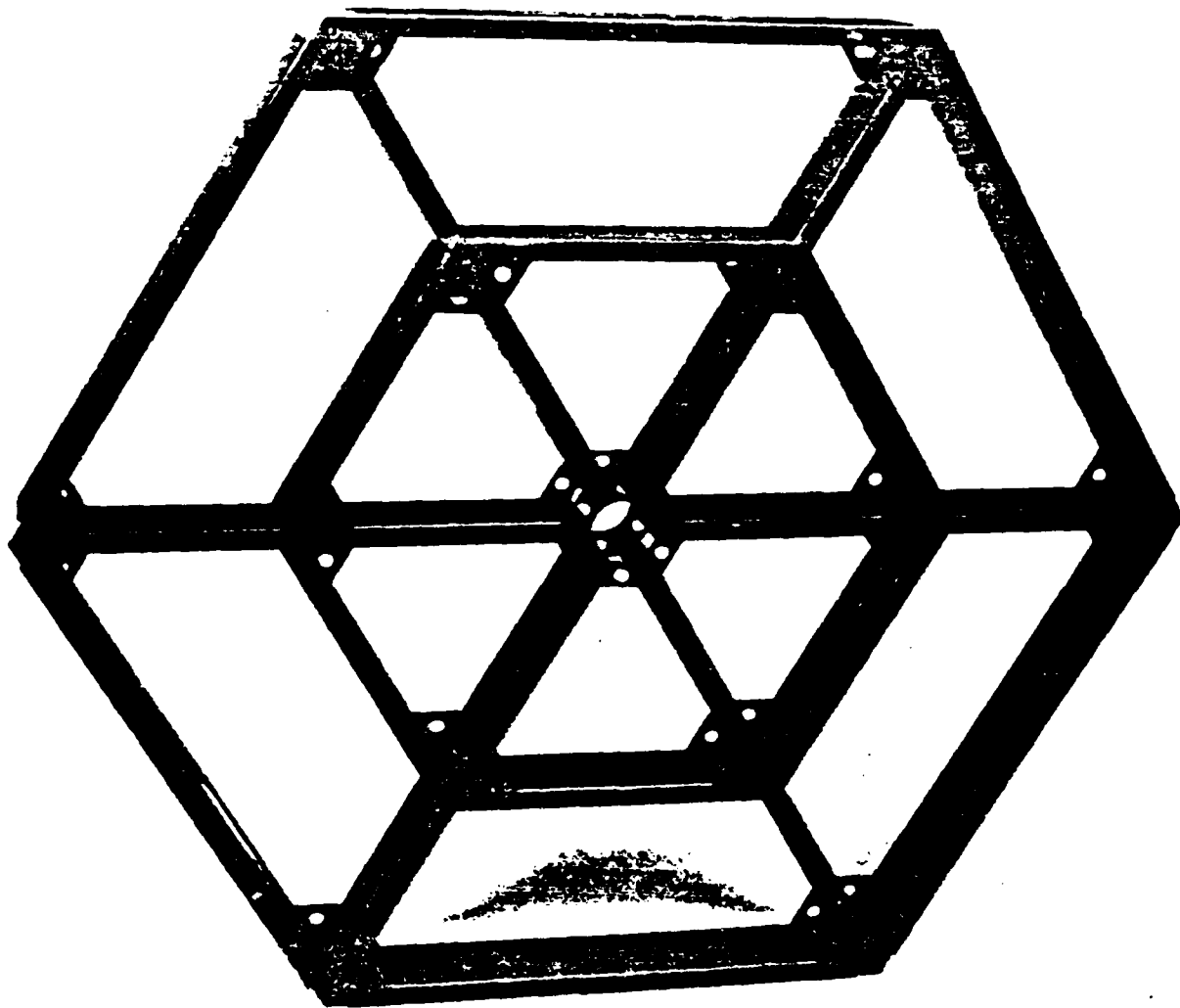


Figure 2. The Basic Structural Subassembly of MHPE is an Hexagonal Box Truss (Hex-Panel) Made of Graphite Epoxy (GrE) Tube with Aluminum End Fittings. The Figure Shows One of the Hex Panels.

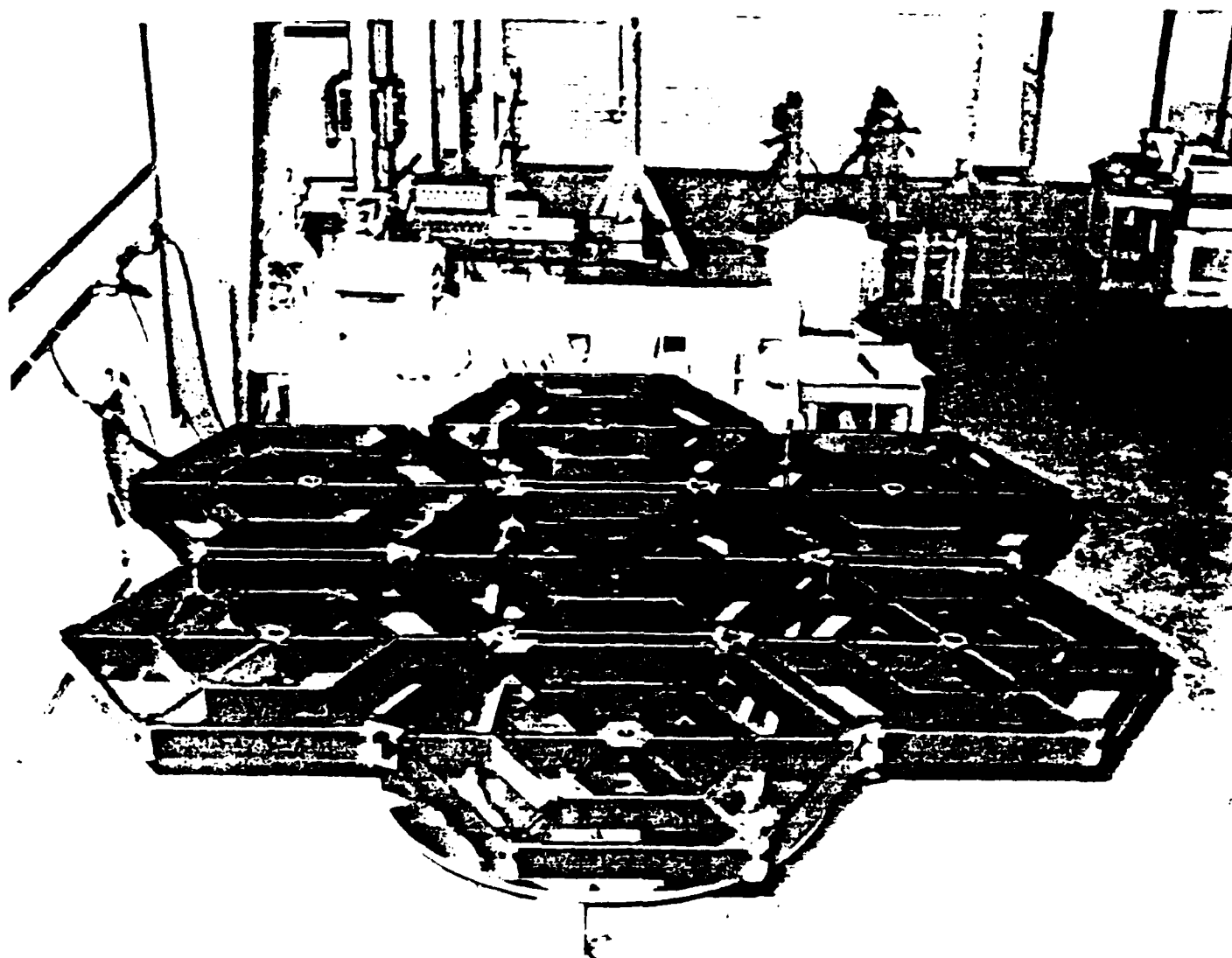


Figure 3. Seven GrE Hex Panels are Assembled to Form the MHPE Array. Photograph Was Taken Prior to Installation of Surface Facets.

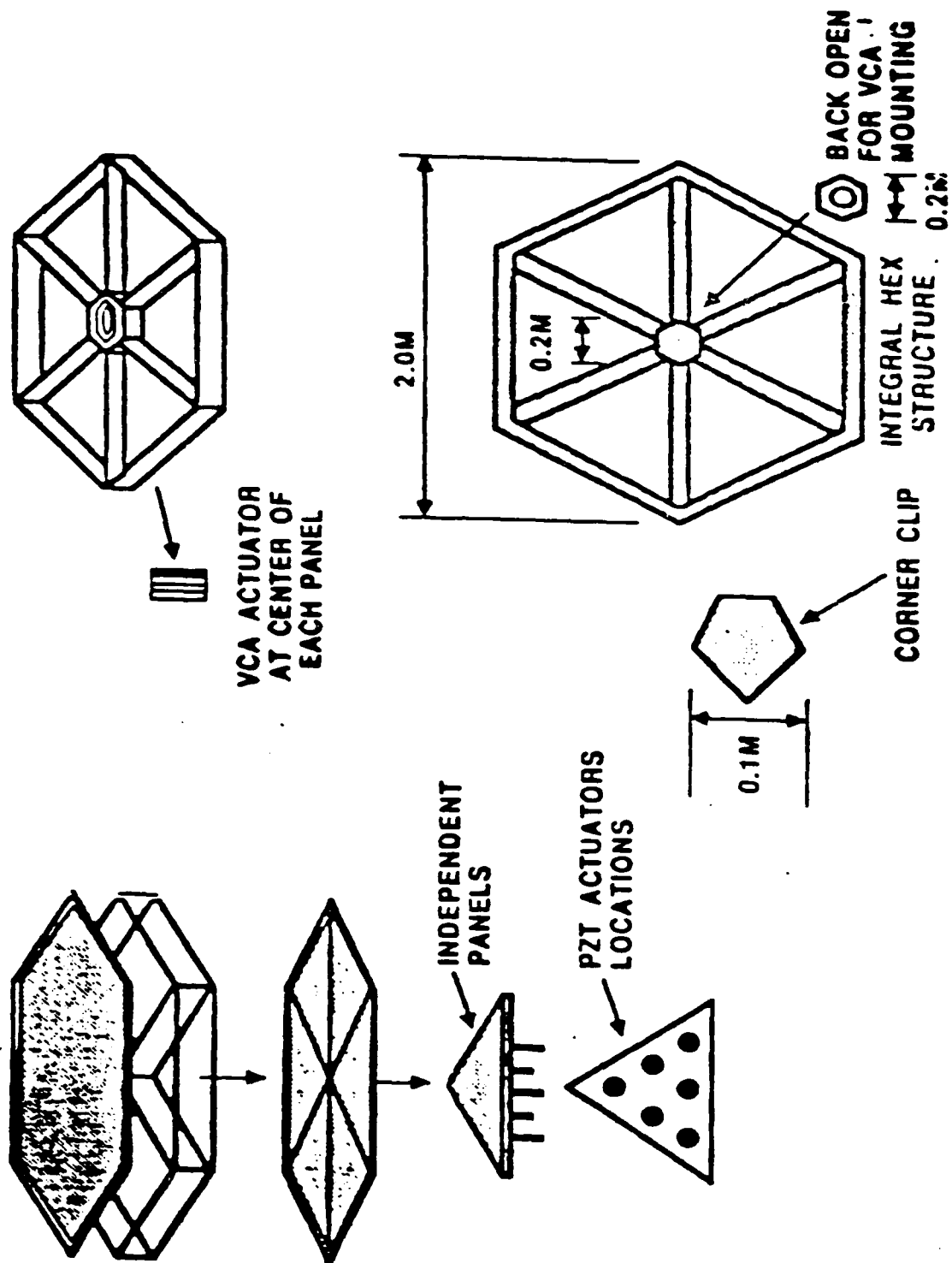


Figure 4. Multi Hex Panel Test Bed — Arrangement of Surface Facets on GrE Hex Panel and Location of LPACT Actuators Within a Panel.

The hex panels form the substrate upon which mirror facets are mounted. As shown in Figure 4, six independent triangular mirror facets are mounted to each of the GrE hex panels with six interface flexures for each facet. For reasonable cost, aluminum honeycomb plates with equivalent mass and stiffness properties were used for the mirror panels. The interface flexures simulate, both in dimensions, geometry and mechanical properties, active PZT surface control actuators. Also indicated in Figure 4 is the manner in which the actuators are mounted. Presently the system has six LPACT units, one per panel, mounted *within* the hex panel at the center. Note that by this arrangement, the control instrumentation is unobtrusive and does not interfere with deployability considerations.

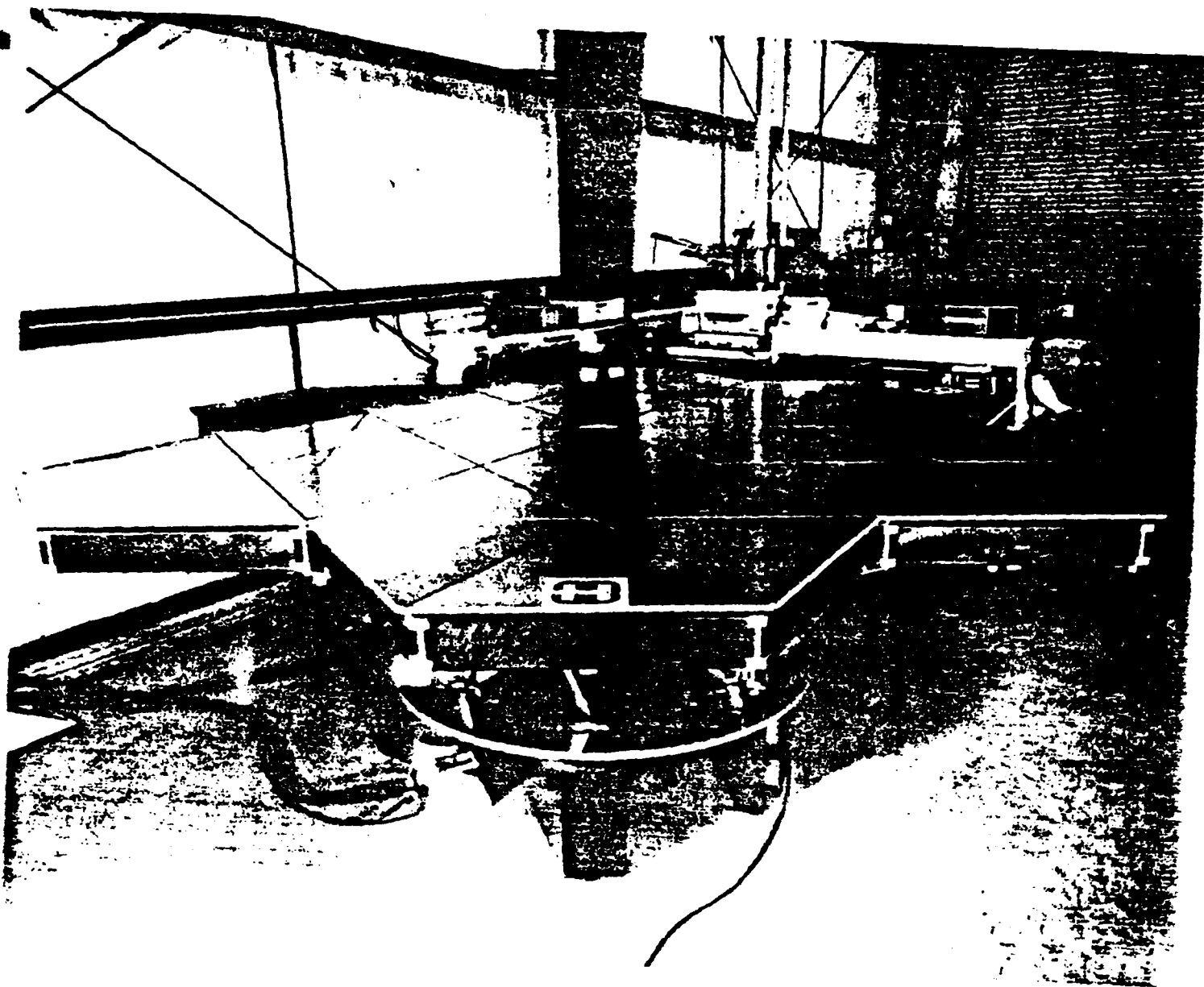
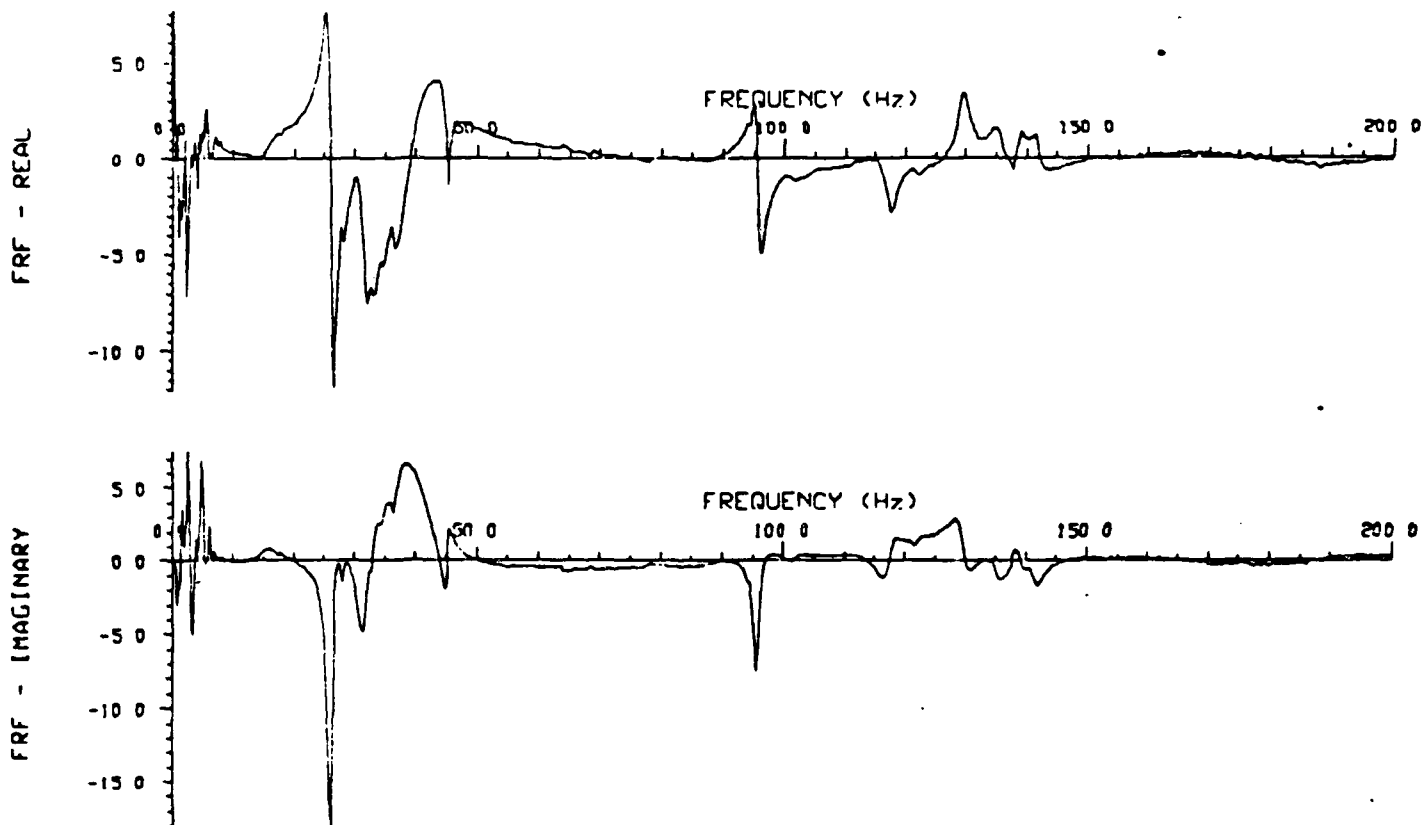


Figure 5. Completed MHPE Test Facility

The complete MHPE structure, including surface panels is shown in Figure 5. Overall, the structure consists of the mirror facets mounted on the surface interface flexures to the 7 panel GrE hex truss array which is, in turn supported by a six member aluminum truss on a circular support platform. The support platform rests on three air-bag isolators (to support the dead weight and isolate from ground vibration) and is interfaced with electrodynamic shakers.

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/ID 2/open loop random excitation 10-200Hz, from shaker #2, no bssels /
/DATAFILE /data/als2nb data /SAMPLE RATE 0 500E+03 /
/FFT PTS 2048/WINDOW HANNING /BLOCKS 24/START TIME 0 00E+00 /
/ACCELEROMETER L1 PRI /-MEAN /



FRF H1 /INPUT 50/OUTPUT 7 (in/sec**2 /lbf)

Fri May 27 19 15 37 1988

Figure 6. Sample of FRF Data Taken During Open-Loop
Vibration Tests of the MHPE

The facility was ready for test in May 1988 and open-loop vibration test data was acquired and used to identify the modal characteristics. Figure 6 shows an example of measured Frequency Response Function (FRF) Data. FRF's were constructed using excitation from all shakers, all six LPACT actuators, and using measurements from all eighteen accelerometers. Using this FRF data (generated by the MCX-5 computer) and a battery of system identification methods implemented at Harris, structural modal frequencies and mode shapes were identified.

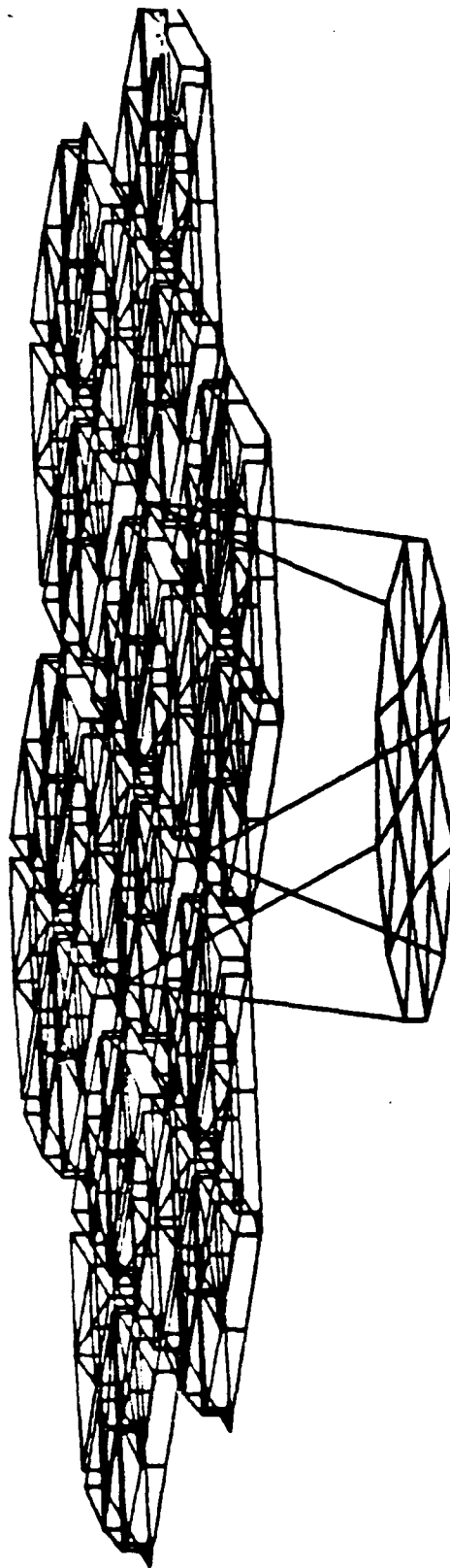


Figure 7.a. MHPE Finite Element Model

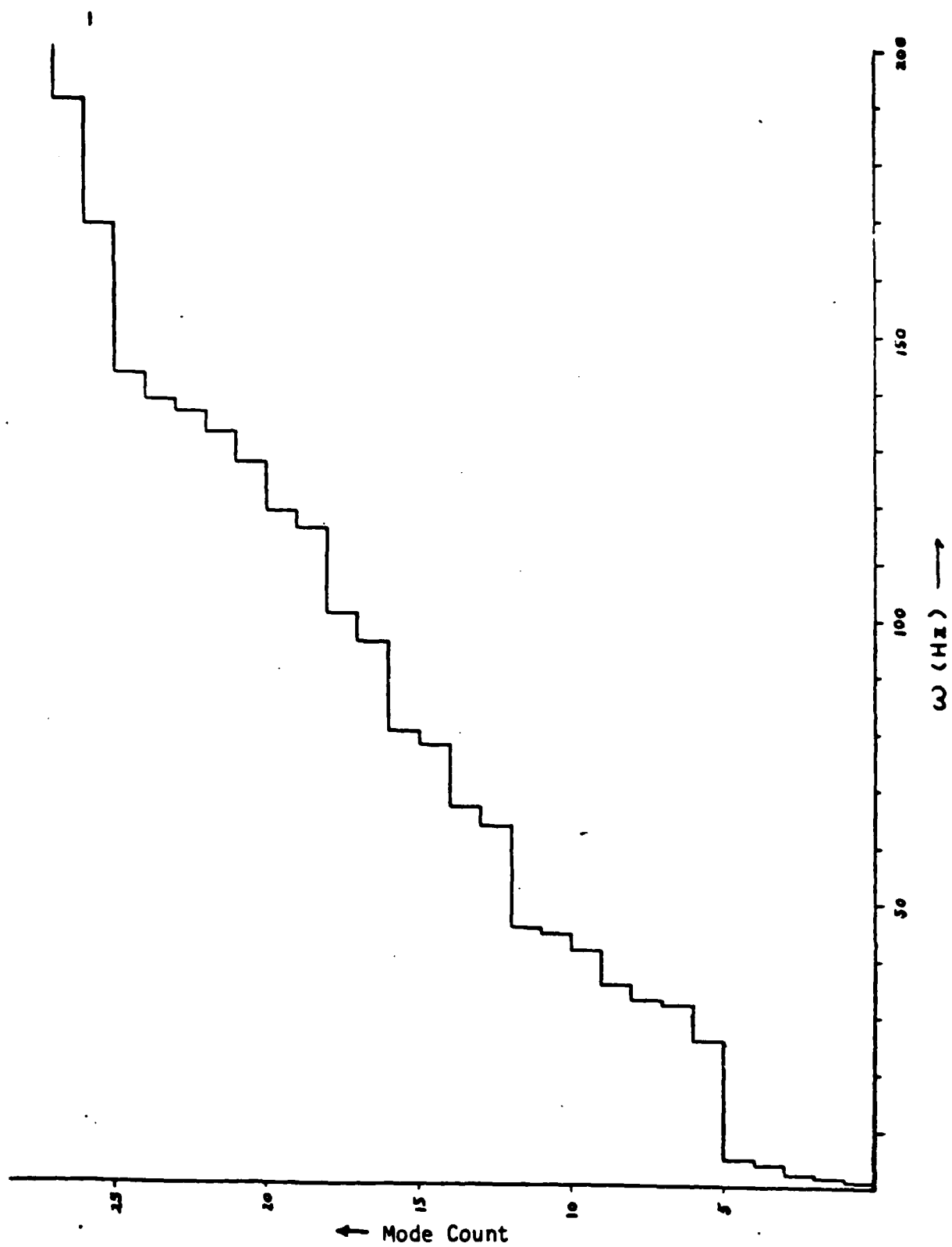


Figure 7.b. Mode Count Versus Frequency for the MHPE Structure

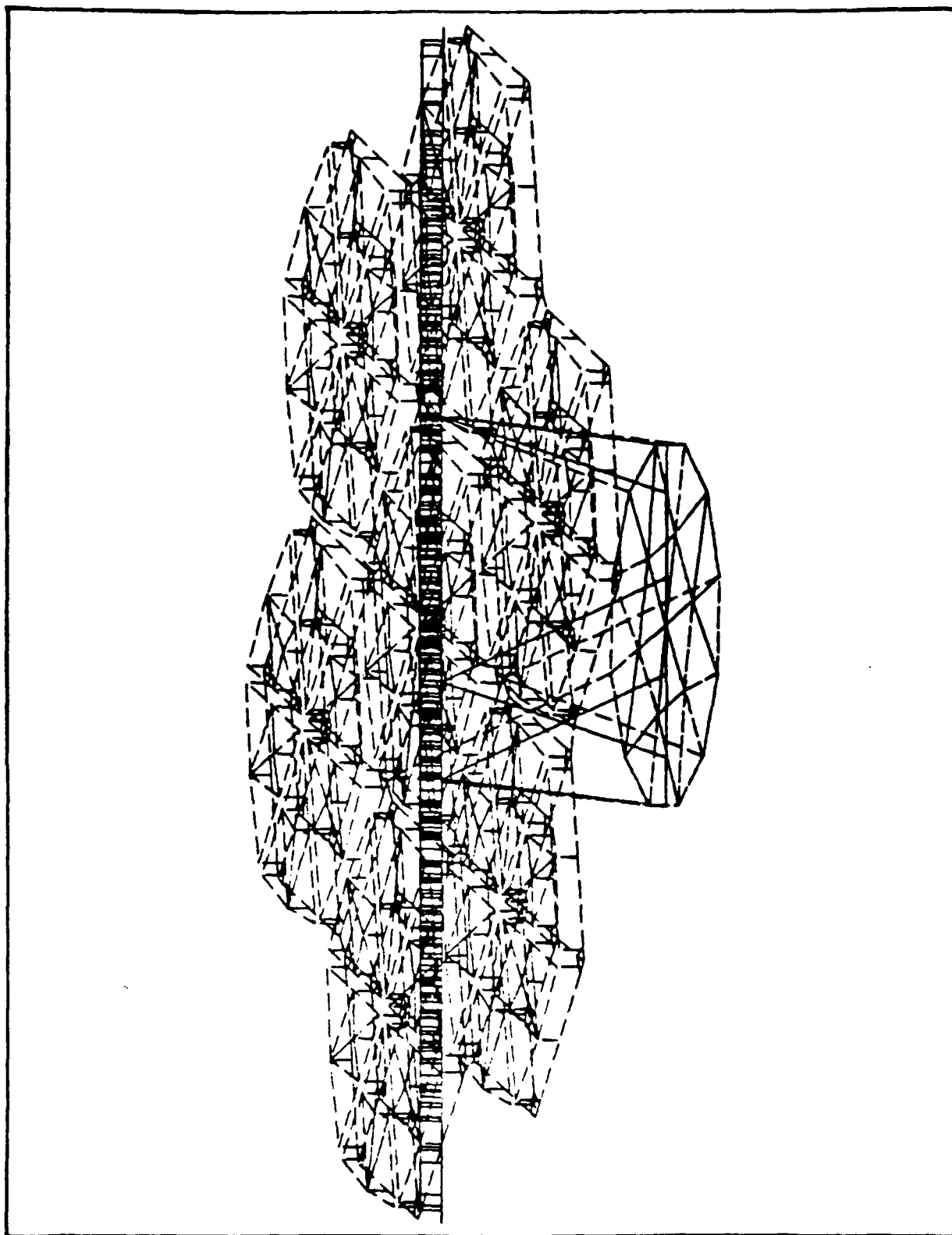


Figure 7.c. Typical "Isolation Mode" Shapes

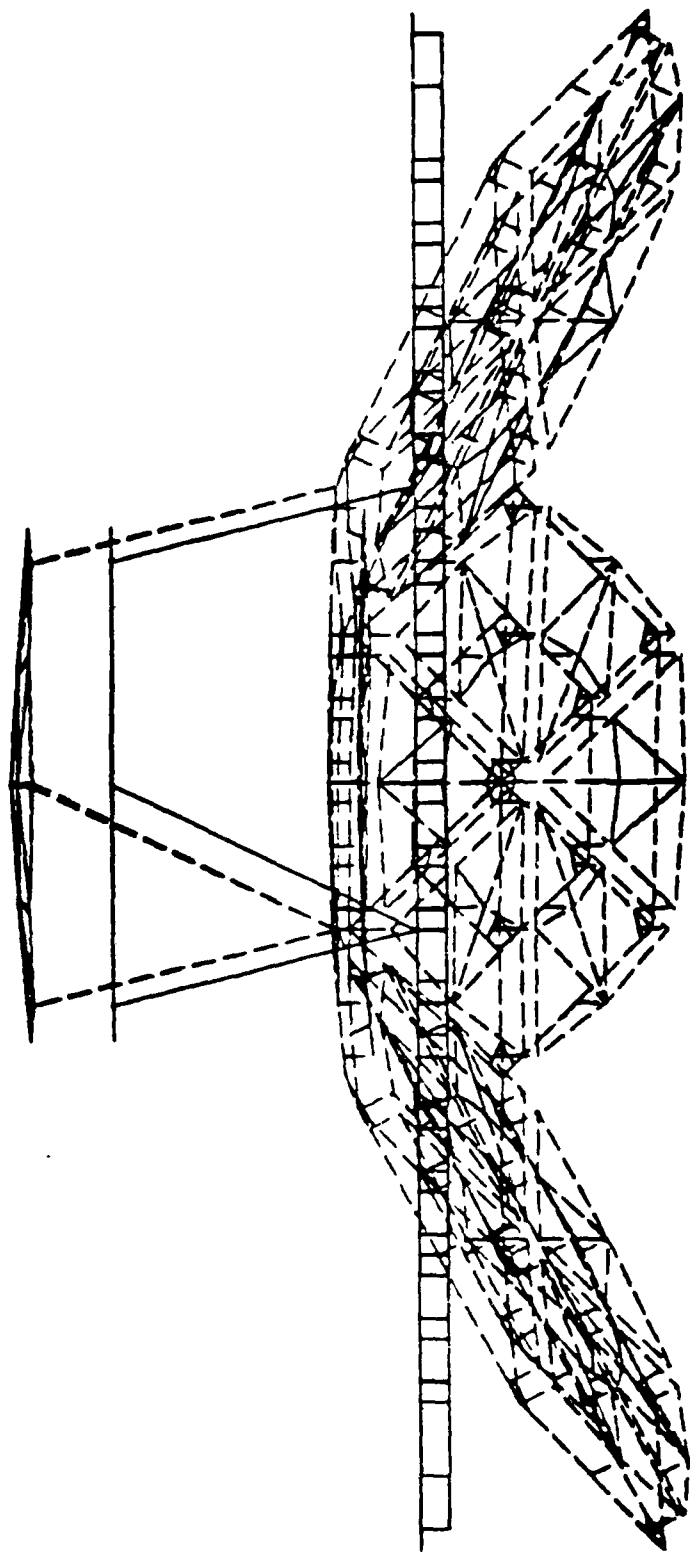


Figure 7.d. First, "Cup", Mode

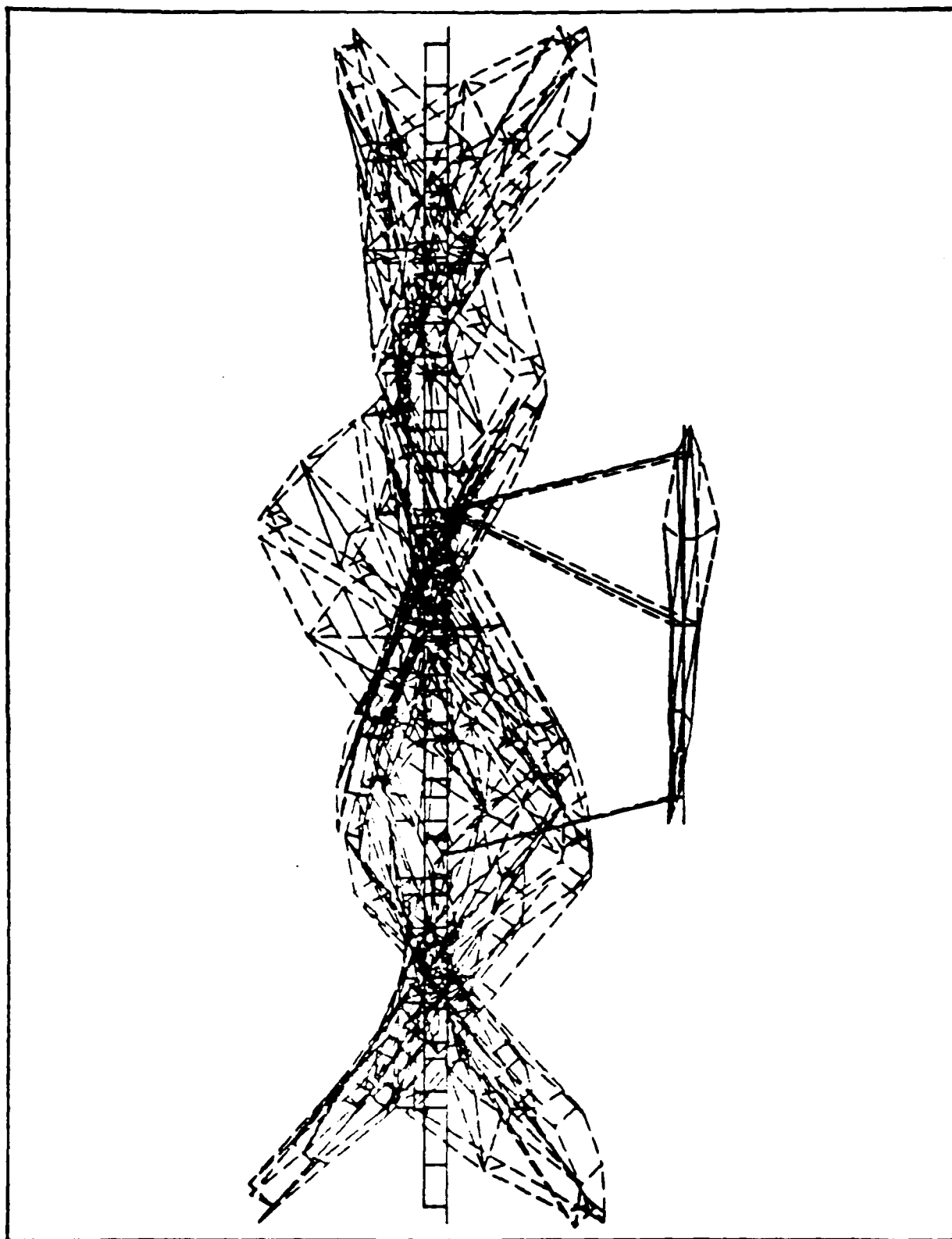


Figure 7.e. Example of a Higher-Order Bending Mode

The finite element model (Figure 7.a) was refined to agree with the system ID results by iteratively refining the values of the more uncertain stiffness parameters so as to achieve a best fit with FRF data. Agreement on frequencies and mode shapes is virtually exact for the first ten MHPE structural modes and errors are no more than 10-20 percent for higher modes below 200 Hz. Figure 7.b shows the identified mode count (number of modes below a given frequency as a function of frequency). It is seen that there are 5 low-frequency isolator modes (excluding the overall torsional mode) involving no contribution to interpanel dephasing. The actual MHPE array structural modes exhibit about the right stiffness and modal density to be representative of the lower portion of a Beam Expander structure (i.e., Primary Mirror, reaction panels, bipod struts and bulkhead). Figures 7.c-7.e illustrate typical mode shapes.

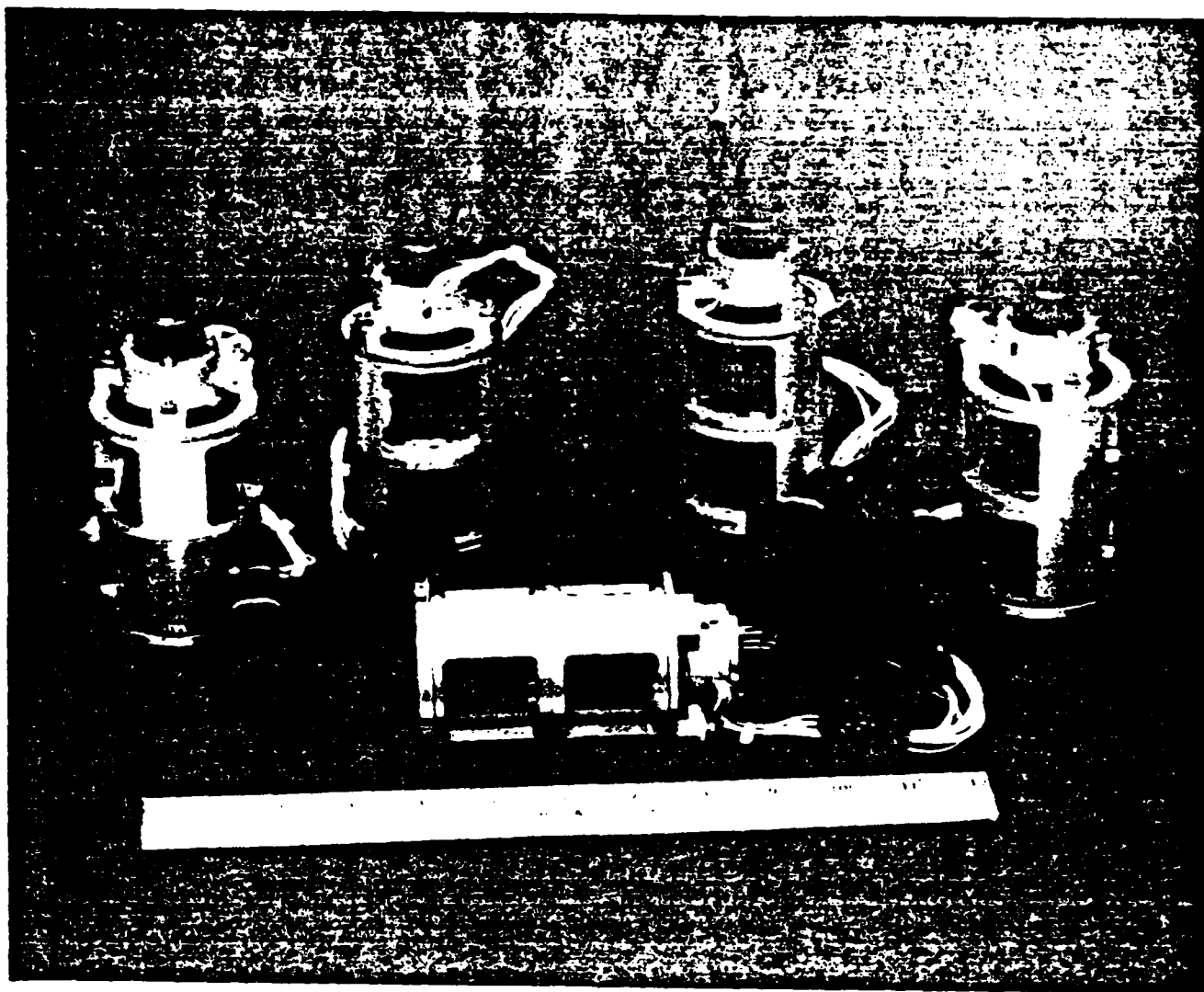
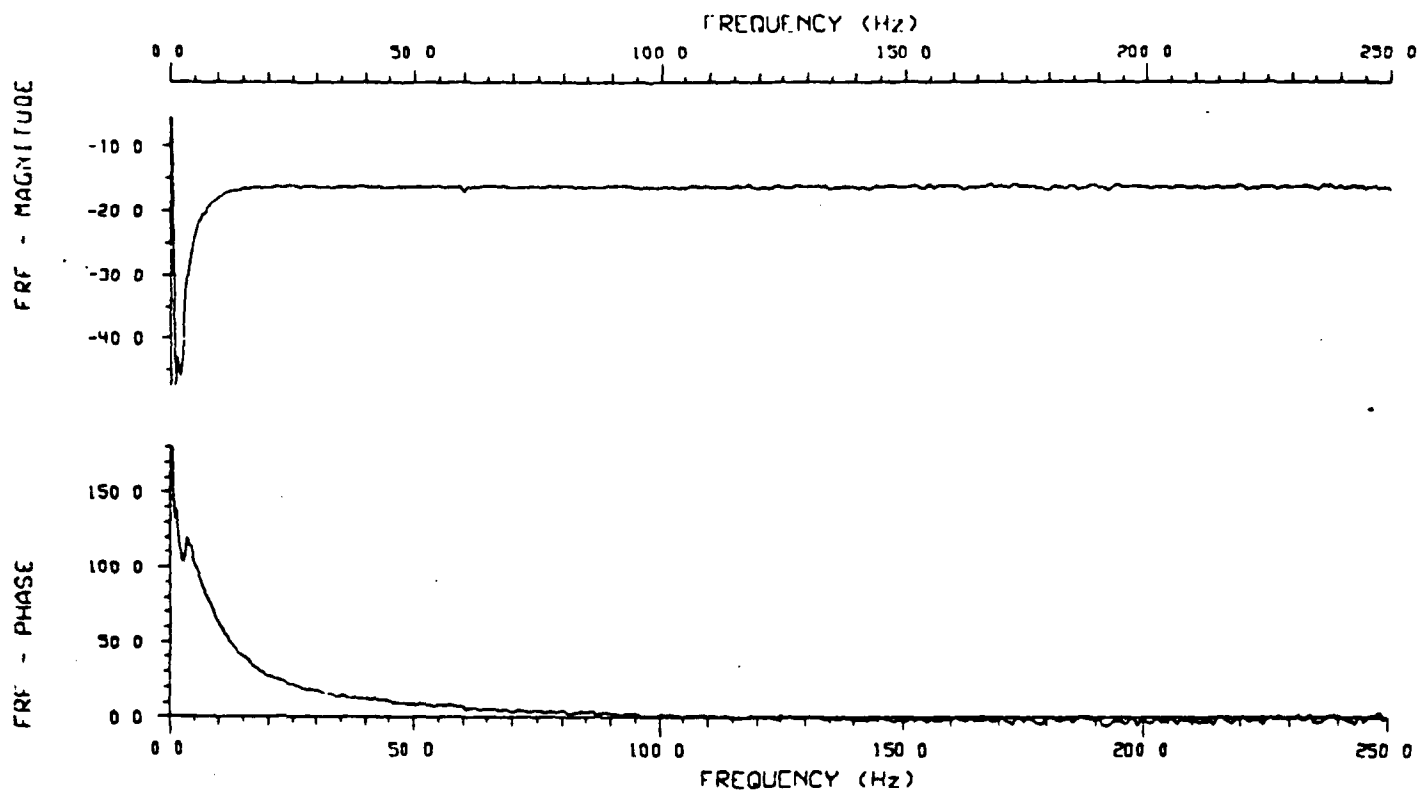


Figure 8. LPACT Actuators for MHPE— Five Out of Six Units Shown

There are six LPACT actuators, one mounted at the center of each of the outer panels. Figure 8 shows five out of six of the actuators. The LPACT actuator is a permanent magnet voice coil design which has several unique features not found in previously developed devices. First, the actuator has no bearings and uses graphite epoxy flexures to support the moving mass secondary which includes the permanent magnet, flux path irons and an inertial accelerometer. Second, the Proof-Mass mounted inertial accelerometer provides feedback to refine output force and provide damping for the secondary spring mass system and override unwanted nonlinearities and temperature dependent effects.



RUNID 4/INPUT 1/OUTPUT 2

Wed May 11 16 25 46 1988

Figure 9. Bench Test Data for the LPACT Command Voltage to Force Output Transfer Function

Measured FRF data for the LPACT is shown in Figure 9. It is seen that because of the internal force control loop, the LPACT frequency response is extremely flat at and above the first MHPE structural mode at 26 Hz. This renders the actuator an excellent device for broad-band damping of the MHPE.

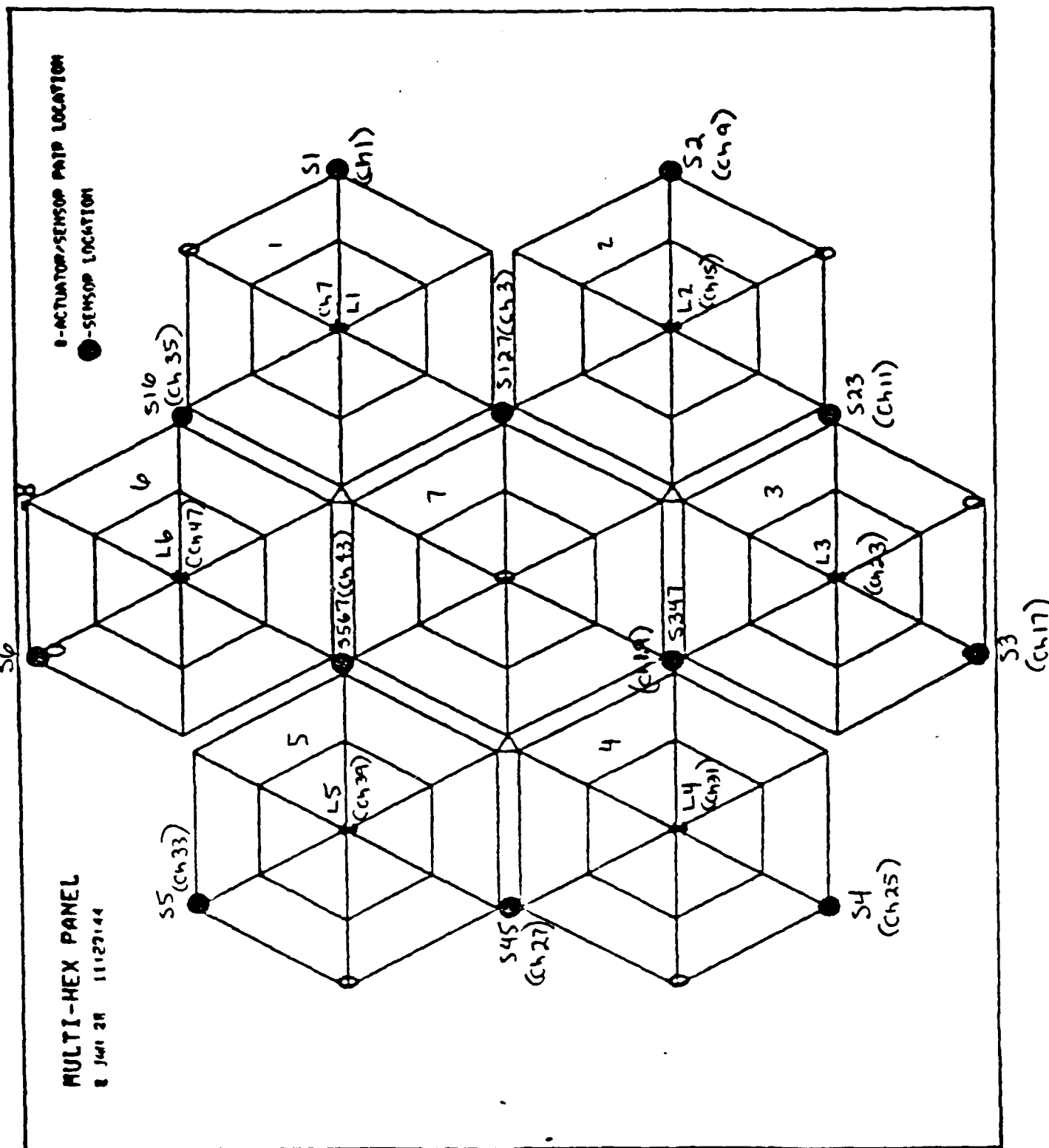


Figure 10. Locations of LPACT Actuator/Sensor Units and Stand-Alone Accelerometers on the MHPE Array

In all, there are six LPACTS, each containing a colocated sensor and twelve stand-alone inertial grade accelerometers distributed over the MHPE (and all mounted *within* the hex panel box trusses) as shown in Figure 10.

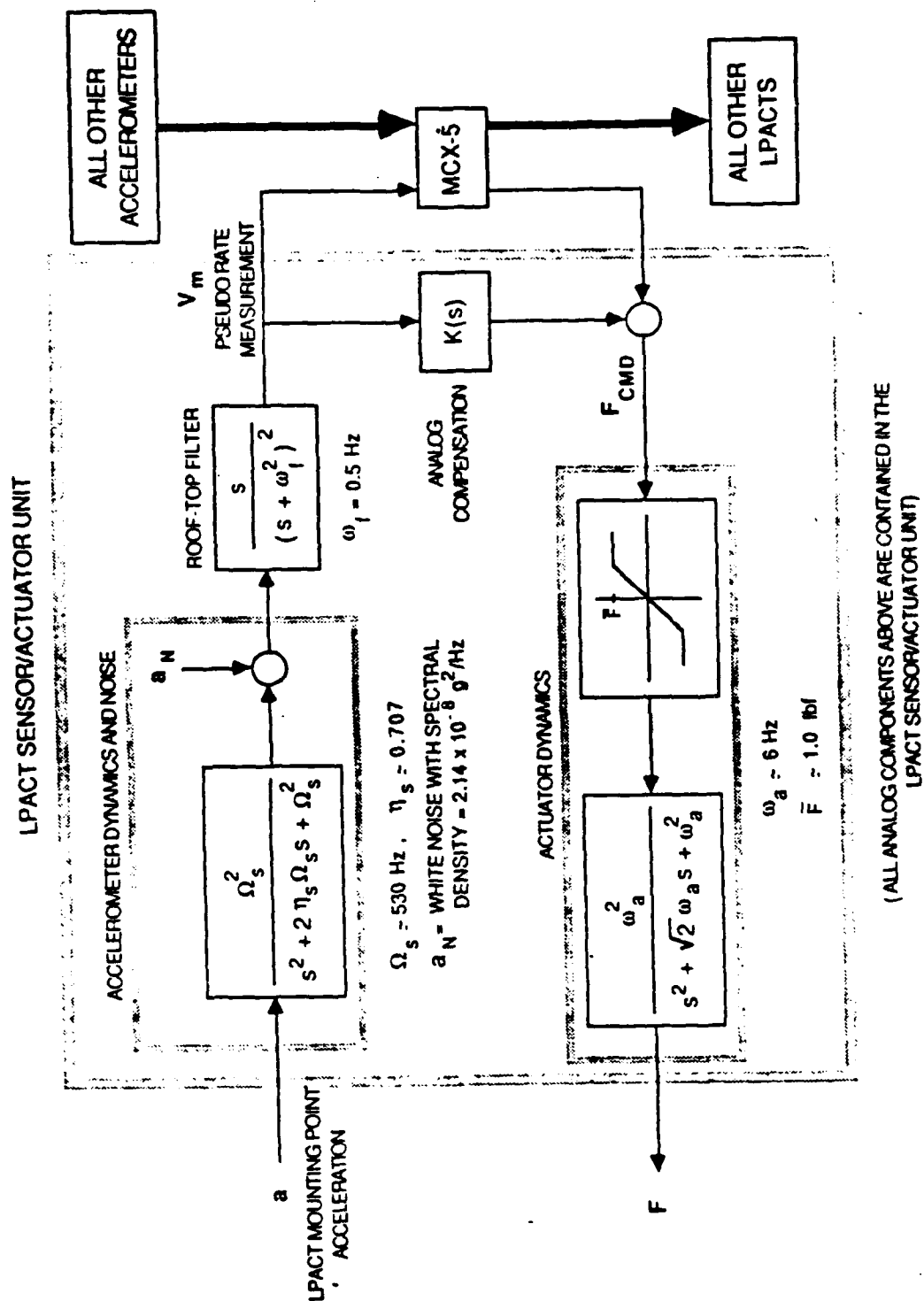


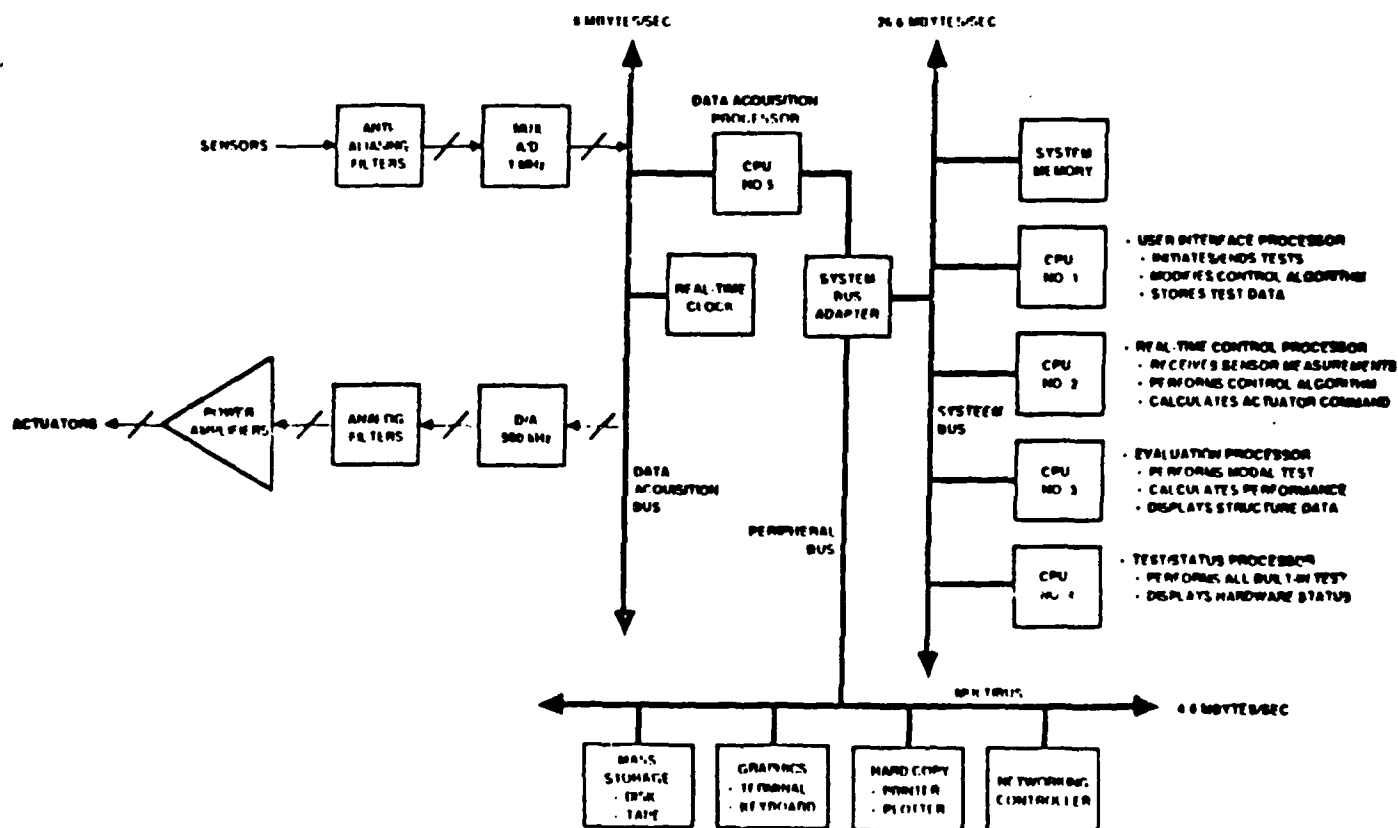
Figure 11. Overall Control Architecture for MHPE, Showing Detail of LPACT Block-Diagram

Figure 11 indicates the control architecture of the MHPE. This consists of independent decentralized output feedback loops in parallel with a dynamic compensator. Note that for MHPE, each LPACT unit contains the actuator, colocated accelerometer and analog compensation (capable of up to an eighth-order compensator) for implementation of a decentralized rate feedback loop. Thus in MHPE the decentralized loops are each completely self-contained within an LPACT unit. In addition, the MCX-5 computer (see below) can implement, in parallel with the decentralized loops, a centralized dynamic compensator.

The isolation system consists of three air bag isolators. Rigid body modes of the MHPE on the stiffness of the isolators are in the vicinity of 2 Hz and the system provides over 40 dB isolation from ground vibration above 20 Hz.

The disturbance system consists of shakers interfaced with the circular support plate and each are capable of an independent broad-band input of up to 10 pounds rms. The shaker disturbance spectra are readily programmable to simulate any desired PSD.

THE HARRIS MCX-5 HAS A MULTIPROCESSOR ARCHITECTURE WHICH IS IDEAL FOR IMPLEMENTING CONTROL AND EVALUATION FUNCTIONS



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Figure 12. The Harris MCX-5 Computer is Used to Provide On-Line Control, Data Acquisition and Data Analysis for the MHPE Facility

The on-line computer for the test facility is the MCX-5 (see Figure 12). This machine offers a very powerful multi-processor architecture for simultaneous on-line control, data acquisition and performance analysis. The MCX-5 has been fully integrated with the apparatus since April 15, 1988.

MHPE SIMULATION BLOCK DIAGRAM

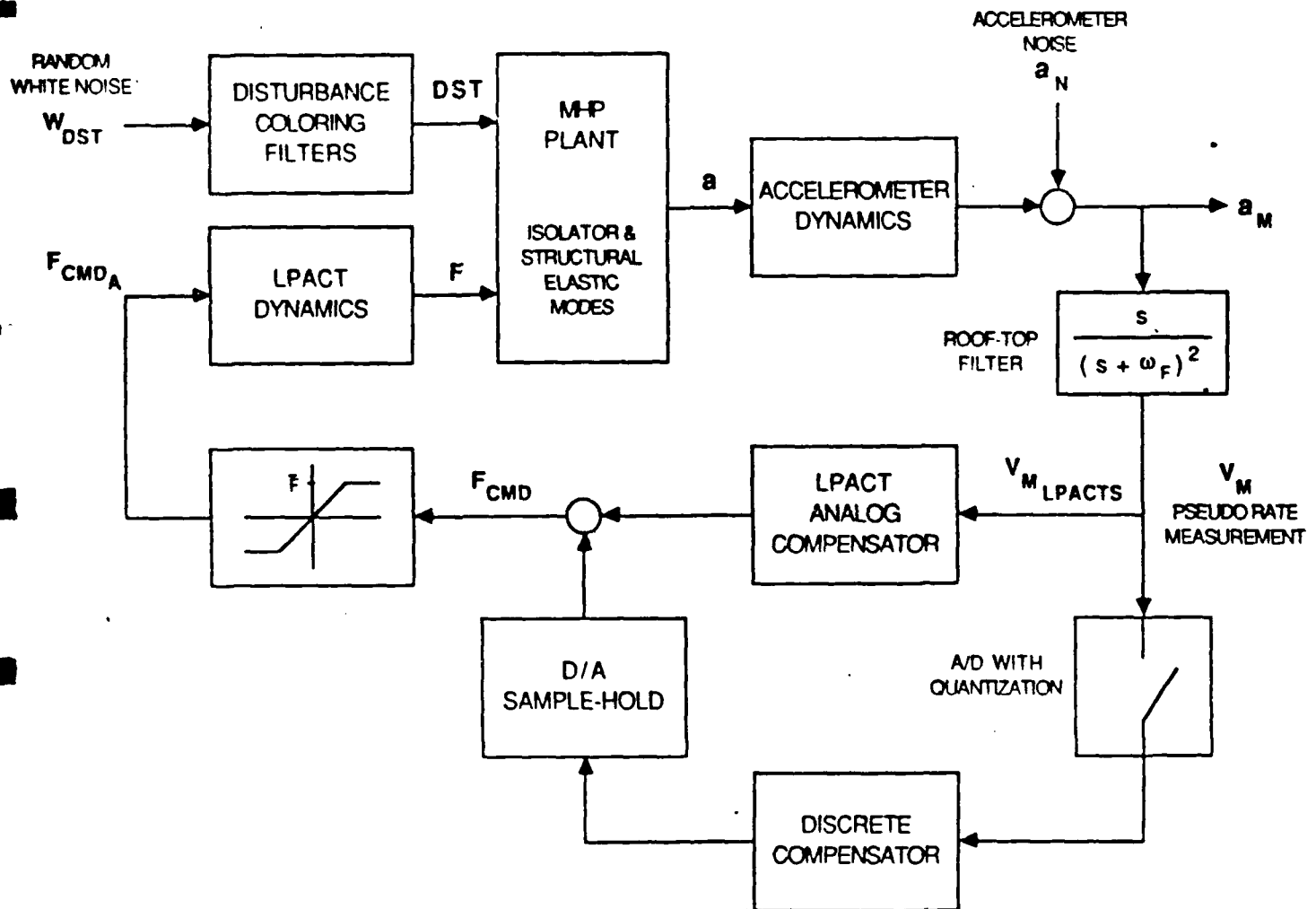


Figure 13. MHPE Simulation Block Diagram

Finally, it should be noted that we have constructed a comprehensive, end-to-end system simulation model for the MHPE. This model (see Figure 13) as been used extensively both for control design synthesis and for design validation.

Figure 14.

Modelling Uncertainties in the MHPE Apparatus

Component	Error Source	Relative Importance
Sensors (Accelerometers)	<ul style="list-style-type: none"> • Bias, Scale Factor, Misalignment, Hysteresis, Non-Repeatability (See Accompanying Table) • Electronics Noise 	<p>Either Unimportant In Regime of Application or Remediable via Compensation & Calibration</p> <p>Important - Sets "Noise Floor" on Performance (Explicitly Included in Analysis & Design Models)</p>
LPACT Actuators	<ul style="list-style-type: none"> • Accelerometer Error Sources • Electronics Variations Due to Thermal Effects • Mech. Fab. Tolerances • Thermally Induced Mech. Properties (Flexure Stiffness Variations) 	<p>Relatively Unimportant (See Accompanying Figure) Because Most Error Sources Are Compensated by Internal Force Control Loop.</p> <p>Electronics Noise (Explicitly Included in Models) is Important to Overall Perf. Accelerom. Mismatch Remedied by Initial Calibration</p>
Structure	<ul style="list-style-type: none"> • Manufact. Tolerance On GRE Tube Thickness • Aluminum Joint Fittings • Epoxy Bond Strength <ul style="list-style-type: none"> • Manufacturing Tolerance On Thickness Of Joint Plates Nominal Thickness = 0.15 in Tolerance = 0.050 in 	<p>Small Absolute Errors Unimportant For Lower Frequency Modes Moderately Important For Higher Modes</p> <p>Very Important - Significantly Affects Even the Lowest Modes</p>

Besides the nominal end-to-end system model, we also provide a description of residual modelling uncertainty. Our survey of likely modelling uncertainties is summarized in Figure 14. It was found that the most important source of modelling uncertainty is the variation, within manufacturing tolerances, of the thickness of the joint plates which tie together the adjacent hexagonal panels of the MHPE mirror array. Such thickness variations can cause over 10% variations in the predicted modes.

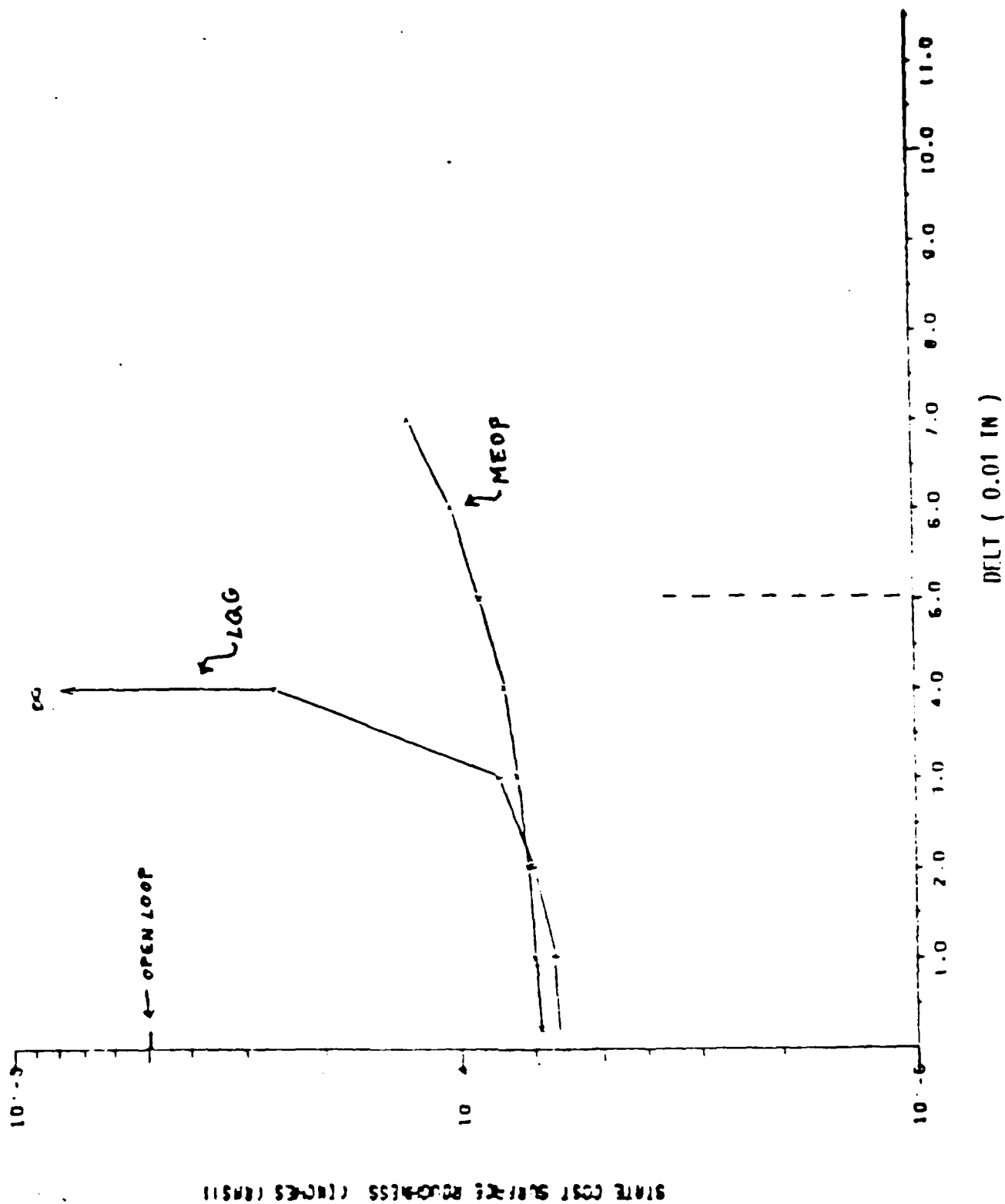


Figure 15.

Using our design and analysis tools we have designed a MEOP vibration control algorithm which maintains good performance despite off-nominal joint plate thickness variations. Figure 15 shows how, under two different controller designs, the mirror panel optical quality (dephasing) degrades as a function of off-nominal joint plate thickness variations of magnitude " Δ ". The manufacturing tolerance is indicated by the dashed line in Figure 15. Note that a standard Linear Quadratic Gaussian (LQG) controller design can drive the closed loop system unstable under worst-case thickness variations. In contrast, the MEOP design maintains excellent performance improvement relative to the uncontrolled structure despite worst-case thickness variations

Appendix B

EVM Program Accomplishments: Time Domain Majorant Analysis for Performance Robustness Evaluation

In order to reduce SDI mission risk and establish a benign system tolerance (*performance robustness*) to critical off-nominal variations in physical parameters and subsystem models, it is necessary to determine quantitatively the worst-case performance degradation (relative to nominal performance) due to off-nominal conditions. Together with nominal design predictions, this information establishes that a design will exhibit desired performance not only under nominal conditions but also under worst-case off-nominal conditions. One of the principal objectives of the EVM study has been to develop, implement and demonstrate advanced performance robustness analysis tools in order to reduce risk and cost for the engineering development of SDI systems.

Before the development of modern performance robustness analysis methods, the determination of worst-case performance degradation would utilize an end-to-end design model and perform an exhaustive simulation study, involving a large number of simulations with numerous simultaneous variations in all parameters. However, the end-to-end SDI system models are typically quite large (200 states) and the number of independent performance-significant off-nominal variations is also large (10-100). Thus the "brute-force" simulation approach is prohibitively time consuming and expensive. In contrast, given the magnitudes of possible independent variations in system parameters, and the nominal system model, Majorant Performance Robustness Analysis (MPRA) can bound the worst-case performance degradation by means of a single calculation involving no more computation than a single simulation run.

MPRA is the application of the work of Dahlquist [1]* and Ostrowski [2] to the determination of performance degradation due to uncertainty or the bounding of off-nominal prediction error due to uncertainty. Thanks to the support provided under the EVM study, MPRA has seen extensive development and application [3-7], and the requisite software has been developed and fully implemented at Harris Corporation.

Basically, MPRA consists of representing the system in a large scale system analysis format, then applying the concepts of the *matrix majorant* and associated non-negative matrix inequalities developed by Dahlquist. MPRA actually gives a sequence of progressively sharper, i.e., less conservative bounds on performance degradation and, in many cases, produces both upper and lower

* Refer to the publications listed at the end of this article.

bounds on the exact worst-case performance degradation. Thus, MPRA bounds are never overly conservative. MPRA has been developed and applied to frequency domain analysis (determining the magnitude of errors in transfer functions due to parametric uncertainties, for example), to time-domain analysis and to statistical response of systems with random disturbances. Time-domain MPRA is probably the easiest to visualize and we illustrate results of this kind here.

To illustrate the capabilities of the time-domain majorants, we discuss an example given in [7]. This example, depicted in Figure 1, considers a tracking problem where a flexible spacecraft with a rigidly mounted antenna must track a target through an encounter which takes 5.0 seconds and covers 180 degrees. To illustrate the system analysis aspects of majorants, we suppose that the tracker control loop was designed taking into account only the rigid body dynamics and that all that is known about the elastic dynamics is that there are modes above 20 Hz with specified bounds on the elastic modal coefficients associated with the tracker sensor and thrusters. Given this rather crude knowledge of the elastic modes, it is required to determine how much the actual closed-loop tracking performance can deviate from the predictions of the nominal, rigid-body model. Thus, we illustrate not only the effects of uncertainty but also the utility of majorants in ascertaining the impact of unmodelled dynamics. The results also indicate how majorant bounds can be used to determine the quality of system identification necessary to support system certification for flight.

Details of the problem formulation and the analytical setup are given in [7]. Figures 2a,b show final results for various cases in which the first-order majorant bound has been applied. In each of these graphs, we show five curves. The central curve is the trajectory predicted by the nominal model which includes only the rigid body dynamics; in addition we plot the nominal trajectory plus or minus the upper bound $\hat{E}(k)$ on the exact worst-case prediction error; finally, we also show the nominal plus or minus the lower bound $\check{E}(k)$ worst-case error $E^*(k)$. Note that despite the uncertain elastic mode effects, the actual system trajectory is certain to lie between the outermost curves. Thus, majorants predict not merely a single trajectory, but rather a "tube" or band wherein the actual trajectory must lie. Furthermore, note that in all cases the curves representing nominal $\pm \hat{E}(k)$ and nominal $\pm \check{E}(k)$ are relatively close thereby indicating that the upper bound on the prediction error entails very little conservatism. In particular, in cases 1, 3 and 4, the curve corresponding to upper and lower bounds are so close together that they cannot be distinguished.

Referring to Figure 2a, in particular, cases 1 and 2 show how increasing the controller bandwidth (from 1.0 Hz to 5.0 Hz) reduces the nominal target error but increases the prediction error for a

TIME DOMAIN MAJORANT EXAMPLE **SPACECRAFT TRACKING EXAMPLE**

- ENCOUNTER DURATION : 5.0 SECONDS
- 180 DEGREES USING THRUSTERS.
- DYNAMIC MODEL: RIGID BODY MODES AND TWO ELASTIC MODES AT 20.0 AND 40.0 HZ
- CONTROLLER SAMPLE RATE: 50.0 HZ

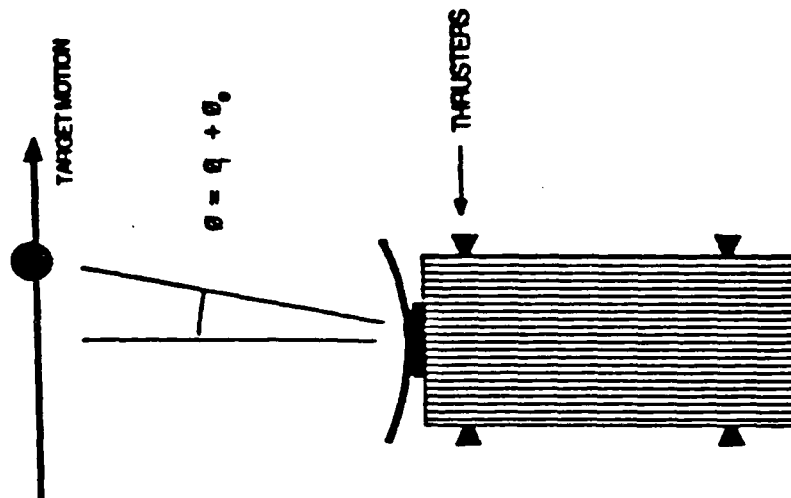
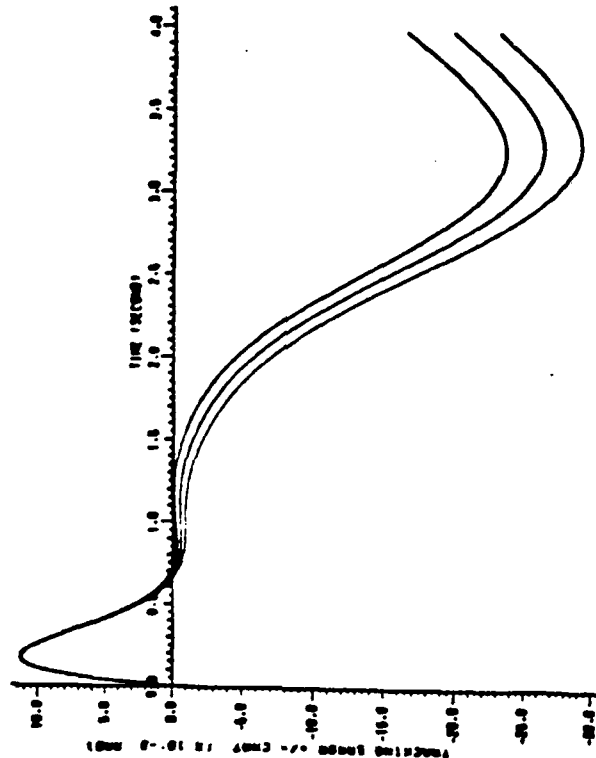
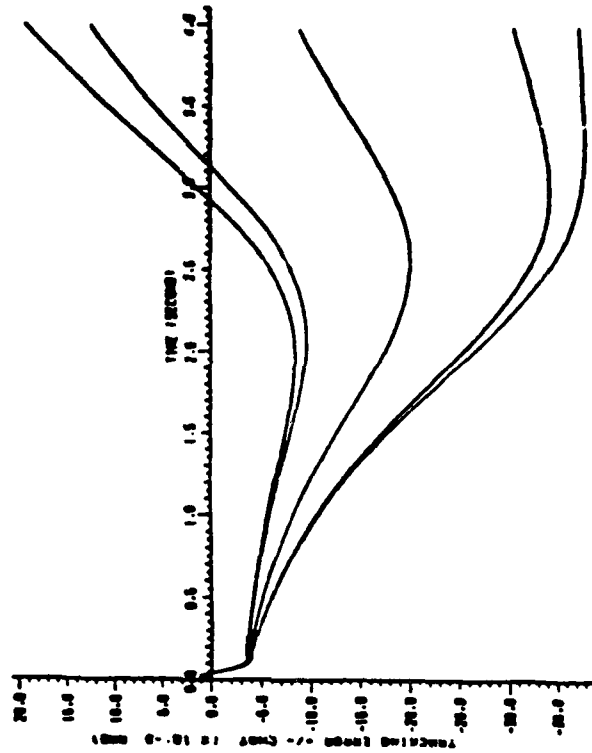


Figure 1. Time Domain Majorant Example

TIME DOMAIN MAJORANT EXAMPLE SPACECRAFT TRACKING EXAMPLE (CONTINUED)



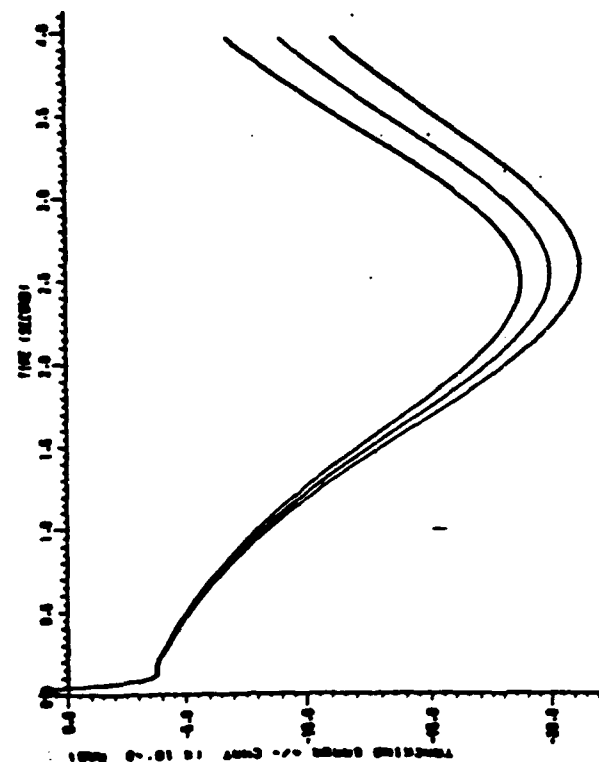
CASE 1: $f_c=1.0$ Hz, NOMINAL UNCERT.



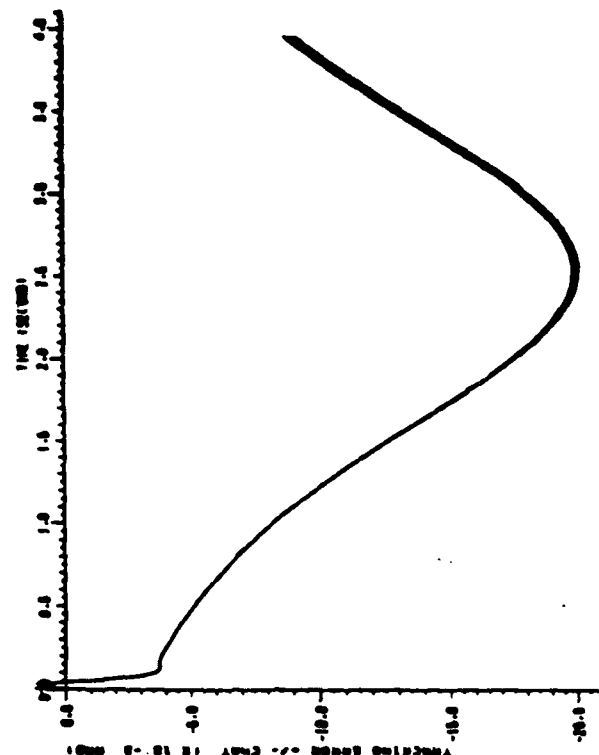
CASE 2: $f_c=5.0$ Hz, NOMINAL UNCERT.

Figure 2(a). Time Domain Majorant Bounds for
Spacecraft Tracking Example

TIME DOMAIN MAJORANT EXAMPLE SPACECRAFT TRACKING EXAMPLE (CONTINUED)



CASE 3: $f_c=5.0$ Hz, 0.1 X UNCERT.



CASE 4: $f_c=5.0$ Hz, 0.01 X UNCERT.

Figure 2(b). Time Domain Majorant Bounds for
Spacecraft Tracking Example (Continued)

given amount of elastic mode uncertainty. This illustrates the use of majorant analysis to help determine controller bandwidths appropriate for the precision of modelling information. Cases 2 through 4 show how decreasing the elastic mode uncertainty decreases the performance bounds. In going from case 2 (Figure 2a) to case 4 (Figure 2b) the uncertainty is reduced by an order of magnitude each time. This shows the capability of majorant analysis to ascertain the precision of system identification that is required to attain a given level of guaranteed performance. In the present example, it is seen that a 20 milli-radan tracking specification would require a system ID test that reduces model uncertainty by an order of magnitude.

The above example illustrates the procedure to be followed (and the kind of results expected) in applying MPRA. Estimate bounds of performance-critical parameter variations, then apply MPRA to get a tube or band containing the nominal system response, and within which the system response *must* lie under all possible worst-case variations. Good robust performance means that the entire tube lies within the desired performance envelope.

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Appendix C

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Appendix D

Program Personnel

Dr. David C. Hyland, Principal Investigator

Dr. Hyland joined Harris GASD in 1983 and heads the Controls Analysis and Synthesis Group. He received the B.S., M.S. and Sc.D. degrees in Aeronautics and Astronautics from Massachusetts Institute of Technology. After serving as a vibration specialist in a Cambridge-based acoustics consulting firm, he joined MIT Lincoln Laboratory in October 1974 where he worked in the areas of reentry vehicle dynamics and spacecraft dynamics and control. In continuance of a longstanding interest in the stochastic modeling of uncertain mechanical systems, he originated the minimum data/maximum entropy modeling technique and the optimal projection approach to fixed-order compensator design. In this connection he is the author of more than 30 research publications. He served as an advisor to the DARPA Active Control of Space Structures (ACOSS) Program and has contributed to numerous DOD and NASA projects.

Dr. J. W. Shipley, Technical Advisor

Dr. Shipley is a senior scientist within the Mechanical Systems Engineering Section of the Mechanical Systems Department. He has 14 years of experience in structural analysis, structural dynamics, design and testing as an individual contributor and technical supervisor. His background is in solid mechanics, and he has numerous publications in the areas of random vibration, fatigue, computer structural modeling, and precision space structure technology. Before joining Harris he worked for Martin Marietta on structural analysis for air defense systems. He holds B.S.E.M., M.S.E.M. and Ph.D. E.M. degrees, all from Georgia Institute of Technology.

Dr. D. S. Bernstein, Technical Advisor

Dr. Bernstein joined Harris in 1984 and is a staff engineer with the Controls Analysis and Synthesis Group. He received the Sc.B. in applied mathematics from Brown University and the M.S. and Ph.D. from the University of Michigan in computer, information and control engineering. From 1982 to 1984 he was staff member at Lincoln Laboratory, MIT, and he is a member of IEEE and SIAM. Dr. Bernstein has more than 25 research publications in the areas of digital simulation and optimization along with optimal, stochastic and robust control. His recent research relating to structural control has focussed on extending the optimal projection approach to a variety of modeling, estimation and control settings, including robust, digital, sampled-data, decentralized and distributed parameter control.

Dr. E. G. Collins

Dr. Collins joined Harris GASD in 1987 and is an Associate Principal Engineer with the Controls Analysis and Synthesis Group. He received the I.B.S. in physics from Morehouse College, the B.M.E. in mechanical engineering from the Georgia Institute of Technology, the M.S. in mechanical engineering from Purdue University and the Ph.D. in Aeronautics and Astronautics from Purdue. Dr. Collins is a member of AIAA and IEEE. His current research interests are related to robust Analysis of uncertain multivariable systems with particular application to large space structures. He is the author or co-author of several publications.

Mr. S. Richter

Mr. Richter joined Harris GASD in November 1985 and is assigned to the Control Systems Group in the Technology Systems Department. Mr. Richter received a B.S. and M.S. in mathematics from Purdue University in West Lafayette, Indiana. He then received an M.S. in electrical engineering from Purdue in 1981 and an M.S. in physics, also from Purdue, in 1983. From 1983 to 1985, Mr. Richter worked for ITT Avionics at Clifton, NJ, where he was primarily involved with the development of algorithms for navigational systems. Mr. Richter's principal areas of research are decentralized control, homotopy methods (as applied to control), and astrophysics and gravitation. He has experience on projects involving pointing and stabilization of large space structures and has numerous publications in most of the major control journals. He has also published in the Astrophysical Journal.

Mr. D. J. Phillips

Mr. Phillips joined Harris Government Aerospace Systems Division in January 1985 as a Lead Engineer in the Systems Engineering Section of the Mechanical Systems Department. Since joining GASD, he has integrated Harris Dynamic Data Acquisition Systems used in the testing and evaluation of Harris' precision space structures. He has worked on the instrumentation analyses for the COFS 1 program and is developing the Dynamic Data Acquisition and Control System used in the real-time control of flexible structures. He holds a B.S.E.E. degree from University of Florida and an M.S.M.E. from John Hopkins University.